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Catamaran wave resistance

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Massachusetts Institute of Technology

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LIEUTENANT, UNITED STATES NAVY

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ABSTRACT

A first iteration computer program developed by Drs. Pien and Strom-Tejsen of N.S.R.D.C. for determining the wavemaking resistance of conventional and catamaran hull forms is updated, consolidated, documented and exercised to produce results of immediate interest to catamaran hull designers. The effect of demihull geometry, design Froude number and hull spacing on wavemaking resistance is demonstrated. Within the constraints used in the investigation, it appears that the range of design Froude numbers from 0.30 to 0.35 in association with non-dimensionalized demihull spacings of 0.26 to 0.34 results in minimum wavemaking resistance. However with the aid of the computer program the designer can obtain information for a wide range of design Froude numbers, hull spacings, and hull geometry (represented by singularity distributions) of his own choosing.

Design waterlines showing hull form geometry at six different design Froude numbers are drawn using Michell thin ship theory. The importance, first stressed by Pien, of asymmetric demihulls in producing symmetric wave patterns for maximum wave cancellation is discussed. Finally, the difficulties found at Froude numbers slightly below the design Froude number where the favorable interference factors occur are pointed out.

THESIS SUPERVISOR: Philip Mandel

TITLE: Professor of Naval Architecture

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The author thankfully acknowledges the very great debt he owes to Dr. Jorgen Strom-Tejsen of N.S.R.D.C. who cheerfully spent many hours in reviewing the original program with the author, and who went out of his way to make the author feel more like a welcome guest than an imposition.

He wishes to thank Dr. Pao C. Pien of N.S.R.D.C., who allowed the author free use of the program developed by Pien, and who also spent much time with the author.

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INTRODUCTION

Introduction

With few exceptions and for many good reasons, the art and the science of large catamaran ship design has long been neglected in the United States. The design and construction of the Navy's new 230-ft. catamaran ASR-21 Class and the interest shown in a 700-ft. special cargo ship, both described in (1), have signaled the end to that period of neglect.

The reasons for selection of a catamaran hull for certain ship types rather than a conventional single hull include the capability for handling large loads at the center of the ship, the high transverse stability, the abundance of deck space, etc., in short, considerations of a non-hydrodynamic nature. To reverse the process, to select a catamaran design on the basis of favorable hydrodynamic characteristics, has not been possible because of the sketchiness of full scale and model test data and, until recently, the lack of a catamaran resistance theory in a form which a naval architect rather than a pure theoretician could use.

For whatever reasons a catamaran design is chosen, it is the business of the naval architect to try to make its resistance as low as possible without penalizing other performance and cost criteria. From the standpoint of purely frictional resistance, making the assumption that frictional resistance can be considered to be independent of residual resistance, the catamaran will inevitably compare unfavorably

with a conventional hull of the same displacement due to the greater wetted surface of the former. It is in the area of the so-called "residual resistance", specifically wave-making resistance, that the catamaran offers the opportunity to reduce total ship resistance to a value competitive with that of a conventional hull.

Reduction of Wavemaking Resistance

Wavemaking resistance can be reduced in two ways if a catamaran design is chosen. The first results from the fact that the two hulls obviously have a better slenderness ratio for the same length and displacement than a single hull, with a corresponding decrease in wavemaking. Linearized wave theory might lead one to believe that if the combined beams and displacements of two demihulls were equal to the beam and displacement of a conventional hull of the same length, the wavemaking resistance would be fifty percent that of the single hull. Several authorities, notably J. T. Everest in his discussion of (6), and R. Tasaki, T. Takahei, and J. L. Moss in (7) show that this is not true, except for very fine hull forms at high Froude numbers and cannot be applied to the fuller forms of conventional hulls. Everest used the results of model tests to show that the fifty percent savings indicated by linearized wave theory could be as little as twenty percent.

The second factor which could reduce catamaran wavemaking resistance is that of favorable wave train interference. The theoretical work of K. Yokoo and R. Tasaki (2) in 1951 and K. Eggers (3) in 1955 pointed the way in this respect, demonstrating the favorable effect which the interference of one demihull's wave train could have on the other. J. Strom Tejsen and P. C. Pien indicate in their discussion of ref. (1) that the possibility exists of reducing wavemaking resistance by forty percent at certain Froude numbers in the .25 to .40 range where wavemaking resistance is a significant portion of the total resistance.

Wavemaking Resistance as a Percentage of Total Resistance

The percentages of total resistance contributed by frictional resistance and wavemaking resistance vary with ship speed. F. H. Todd in his chapter on "Resistance and Propulsion" in (4) states that experiments have shown that frictional resistance accounts for eighty to eighty-five percent of the total resistance in slow-speed ships and as much as fifty percent of the total in high speed ships. It is easy to compute (6) that for the same length and displacement the increase in the wetted surface, and hence frictional resistance, will be on the order of forty percent to fifty percent greater than that of a single hull. For this reason

many investigators have concluded that catamarans will always operate at a disadvantage when compared with conventional hulls except for certain very high speed ranges. However, as Pien points out in (5) and Todd in (4) for conventional ships, that while it is true that even eliminating wave drag completely for low speed ships would not affect total resistance drastically, another facet is often overlooked. If ship length can be reduced while keeping the speed and displacement constant, the wetted surface and frictional resistance will be reduced. Reducing ship length and keeping speed constant will increase the Froude number. Wavemaking resistance will increase, but if that increase can be minimized - and the opportunity for doing so by wave cancellation is even greater with a catamaran design than with a conventional design - then the architects could achieve a decrease in frictional resistance of the price of a smaller increase in wavemaking resistance. Of course, as ship speed increases and the wavemaking resistance approaches greater than fifty percent of the total resistance the benefit of wave cancellation is more direct.

Additional Resistance Factors

When two demihulls, each symmetrical about its own centerplane, are separated by an infinite distance, neither

hull will be affected by the presence of the other and the design of the hulls can proceed in the traditional manner. As the hulls are brought closer together and if the form of the hulls, optimized at infinite separation, is unchanged, the flow characteristics in the area between the two hulls will change. The contraction in the cross sectional area between the two hulls will result in the changes in water velocity and pressure normally associated with a venturi effect. That is, there will be a rise in the water level between the hulls, and water will flow under the turn of the bilges and across the bottom of the two demihulls (8). In effect the flow around the two hulls is no longer symmetrical. K. Eggers (3) attributed the increase in resistance exceeding that predicted by theory as hull spacing narrowed to be due to the increased fluid velocity between hulls. The increase in water level between the hulls would also have an effect on frictional resistance. In addition, the larger change in pressure aft of the maximum beam would seem likely to encourage flow separation, although this effect has not been investigated. Finally, there is the question, not yet answered, of the effect of wave reflection between hulls, and the losses due to wave breaking at the centerline of the catamaran where the interior wave trains from the two demihulls will meet.

Asymmetry

Turner and Taplin (1) built and tested an asymmetrical design in an attempt to reduce the wave building between the two demihulls. The side facing inboard on each demihull was made perfectly flat. They recognized that an asymmetrical hull as a cambered lifting surface might be penalized by induced drag. They measured the "lifting force" - athwartships force - while varying spacing hoping as the hulls moved into closer proximity that some of the lift, and hence drag, would be destroyed. They found this effect to be negligible, and concluded that asymmetrical hulls are likely to have unacceptably high resistance. The point which seems to have been overlooked is that the best shape of the inboard sides is not flat - the flow must adjust to the angle of entrance - so that the streamlines entering the area between the two demihulls are no longer straight, but curved outboard relative to each hull. This effect increases as spacing decreases.

J. T. Everest (9) uses a method of linear superposition of measured wave patterns for a single hull to obtain the wave pattern for two closely spaced demihulls. He found good agreement between the results of this method and those obtained from thin ship theory, but found discrepancies between these data and those obtained experimentally.

Experimental data were obtained by using the single hull form from which the wave patterns were obtained (and to which the thin ship theory was applied) as the demihull of a multihull configuration and making the usual resistance tests of the multihull. Everest attributes the discrepancies to non linearities in the actual wave train superposition, to viscous interference, to changes of wetted surface, and to other causes. However, his method and that of Eggers rely upon the assumption of symmetrical flow around each demihull and a symmetrical wave pattern for each hull. It seems likely, therefore, that deviations in practice are due, at least in part, to the introduction of wave pattern asymmetry by the use of two closely spaced symmetrical hulls.

Model tests have demonstrated many of the unfavorable aspects of the asymmetrical flow associated with symmetrical hulls, the increased flow velocities and the increased surface area between the two demihulls which give greater frictional resistance, the disruption of smooth flow along the turn of the bilge and subsequent cross-flow across the bottom, the higher water level between the hulls and resulting interference with the cross structure, and the increased possibility of boundary layer separation because of the greater adverse pressure gradient found between the hulls. In addition, however, the theoretically predicted benefits of wave train cancellation between the interior and exterior

divergent wave systems can only be achieved by interior and exterior waves of the same amplitude. This requires symmetrical flow. Each demihull must be cambered in such a way as to give a symmetrical wave pattern. This camber will be a function of every factor which affects the streamlines - spacing, design speed, and hull dimensions.

Wave Train Interference

In a single hull ship, diverging waves carry off the energy which created them and the energy is not recoverable by the ship. In theory, some of the energy carried by the transverse wave system can be recovered by judicious choice of ship length and speed. In practice optimum cancellation has been difficult to achieve because the boundary layer at the stern reduces the pressure rise there and so reduces the crest height, and by increasing the effective ship length, introduces a phase shift. (Some investigators - notably Inui, have allowed for this effect empirically with gratifying results.)

Catamaran ships, on the other hand, can also cancel part of the resistance due to the diverging wave system. J. T. Everest (9) states that the most beneficial interference effects are obtained for strong diverging wave systems. He reasons thus from the comparison of theoretically pre-

dicted wave drag plotted as a function of Froude number and a graph due to Wigley showing the percentage of total wave resistance due to diverging waves. The phasing is very similar.

Favorable interference between the transverse wave systems of two unstaggered hulls is obviously impossible since both are in phase, and can only interfere destructively. Beneficial interference can only occur in this case between the wave systems of the same hull. Staggered hulls are another possibility.

Reduction of Wave Drag of Each Hull

Wavemaking resistance is proportional to the square of the wave amplitude. A small amplitude wave system can be obtained in the following ways:

1. Minimizing the forebody wave resistance.
2. Relying upon interference between forebody and afterbody wave systems to minimize the total rather than component bow and stern system amplitudes.

Pien and Strom-Tejsen in (10) list several compelling reasons for minimizing the wavemaking resistance of the forebody alone. First, the major portion of the wavemaking resistance is generated by the forebody, that of the after-

body being suppressed by viscous effects. Secondly, wave-resistance theory rests upon the assumption that the free surface effects generated by the disturbance are small. To generate large disturbances in the forebody, and then cancel them by equally large disturbances in the afterbody is obviously stretching the theory. Lastly, the theory assumes that the viscosity effect is negligible, an assumption not valid in the afterbody section.

The fact that viscosity effects change the effective length of the ship, and hence the phasing of the stern wave with respect to the bow wave has been noted. To accept high forebody wavemaking in the expectation that it will be cancelled by that of the afterbody cannot be justified once viscosity is taken into account.

The most promising and valid approach to the solution of the problem seems to be the optimization of the forebodies under suitable restraints (to avoid a ship displacement of zero, for example) taking into account the interference of the two interacting demihull wave patterns.

PROCEDURE

Procedure

Summary

Pien, enlarging upon the work of Inui, has developed (11) a computer program which can be used either to calculate the wave resistance of a given singularity distribution or, by operating under one or more restraints on ship dimensions, can compute the optimum distribution for certain singularity elements together with certain other given elements which together will yield a minimum wave resistance. Pien, in collaboration with Strom-Tejsen, published in 1968 (12) a hull form design procedure for single hulled high speed displacement ships based on this computer program. That same year, in his discussion of the Turner and Taplin paper (1), Strom-Tejsen extended the program's applicability to catamarans. It is that program, simplified, consolidated and brought up to date by the author under the tutelage of Dr. Strom-Tejsen and Dr. Pien, that forms the core of this thesis.

Assumptions

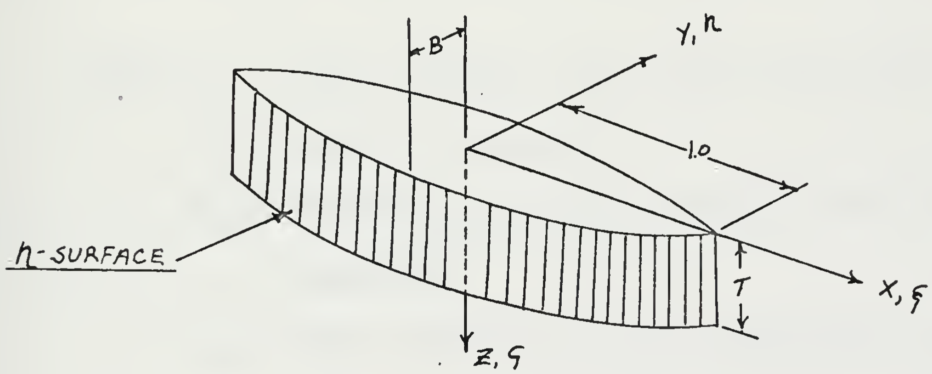
Wavemaking resistance theory, "thin ship theory" rests on two assumptions. The first is that the wave height of the disturbances set up by the moving ship is small in

comparison with wave length, and the second is that viscous effects, are negligible. One of Pien's contributions was his recognition that although a "thin ship" generated wave heights small in comparison with the wave length, and so was sufficient to satisfy the assumption, it was not a necessary condition. If a conventional hull could be optimized so that it too generated small wave heights, thin ship theory could be applied with equal justification. Pien further asserted that since viscous effects on the wave drag of a ship's fore-body are, for all practical purposes negligible, and since the viscous effects present in the afterbody reduce the importance of wavemaking compared with that of the forebody, the second assumption could be met by optimizing the forebody first and then matching an afterbody to the forebody. Some investigators (12) have chosen a Taylor's Standard Series afterbody on the grounds of its known suitability (avoidance of flow separation, etc.). This approach could not be used in a multihull design problem because of the requirement for hull camber. Pien applies wave theory to the afterbody using the following argument. Considering the extreme of no viscous effect, wave theory is valid and the match between afterbody and forebody can be made an optimum. Considering the extreme of a very large viscous effect, which causes the effective afterbody length to be greatly increased, the wavemaking ability of the afterbody will so diminished as to be negligible. The true case will lie somewhere between

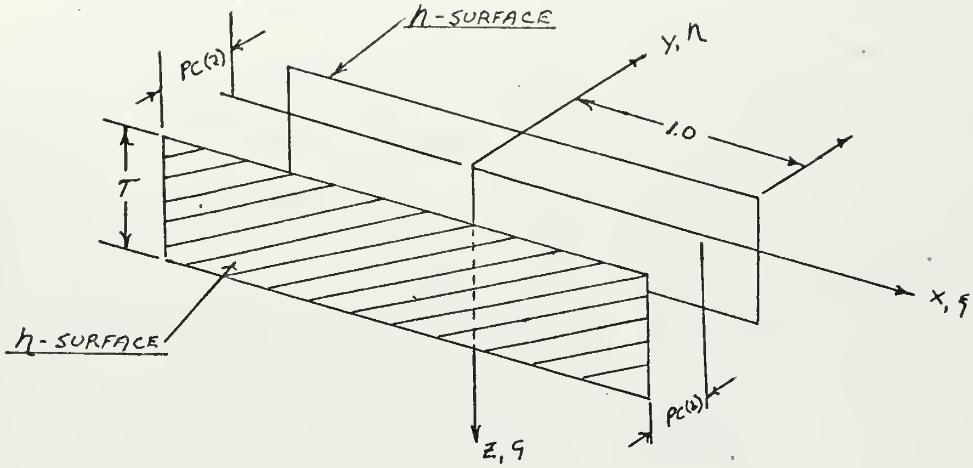
the two extremes. Optimization of the forebody by itself also insures that one does not make the error of achieving a low wave resistance by cancelling a strong bow transverse wave with a strong stern transverse wave which, for the reasons stated above, does not exist in reality.

Mathematics of the Program

Inui placed the singularity distribution on a centerline plane. The disadvantage of this was the limitation of B/T values to less than 2.0 and a sagging keel line. To overcome this, Pien defined an "eta surface" according to the following scheme:



Catamaran demihulls are by their nature long and narrow, and the B/T and keel line characteristics of Inui's system are perfectly acceptable. Accordingly Pien's "eta surface" was modified to give two Inui "centerline planes."



Wave resistance can be expressed as a function of free wave amplitudes as follows:

$$R_w = \pi \cdot \rho \cdot V^2 \int_0^{\pi/2} ([A_c]^2 + [A_s]^2) \cos^3 \theta d\theta \qquad [1]$$

where θ = angle between wave direction and x axis

V = speed of advance

A_c = cosine contribution to the amplitude function

A_s = sine condition to the amplitude function

and for a source distribution

$$A_c(\theta) = \frac{1}{2} \sum_i \sum_j a_{ij} \frac{K_0}{\pi} \sec^3\theta \int\int_\eta \xi^i \zeta^j e^{K_0 \zeta \sec^2\theta} \cdot$$

$$[\cos(a\xi + b\eta) + \cos(a\xi - b\eta)]\, d\xi d\zeta \qquad [2]$$

where F = Froude number

$$K_o = 1/2F^2$$

$$a = K_0 \sec\theta$$

$$b = K_0 \tan\theta \ \sec\theta$$

$$a_{ij} = \text{constant}$$

and $$A_s = \frac{1}{2} \sum_i \sum_j a_{ij} \frac{K_0}{\pi} \sec^3\theta \int_\eta \int \xi^i \zeta^j e^{K_0 \zeta \sec^2\theta} \cdot$$

$$[\sin(a\xi + b\eta) + \sin(a\xi - b\eta)] d\xi d\zeta \qquad [3]$$

simplifying:

$$[\cos(a\xi + b\eta) + \cos(a\xi - b\eta)] = 2 \cos b\eta \ \cos a\xi$$

$$A_c(\theta) = \sum_i \sum_j a_{ij} \frac{K_0}{\pi} \sec^3\theta \int_\eta \int \xi^i \zeta^j e^{K_o \zeta \sec^2\theta} \cdot$$

$$\cos b\eta \ \sin(a\xi) d\xi \ d\zeta \qquad [4]$$

At this point several decisions must be made.

(1) the range of i

(2) the range of j

(3) the form of η.

The singularity distribution to be located on the η surface can be expressed as

$$M(\xi,\zeta) = \sum_i \sum_j a_{ij} \xi^i \zeta^j$$

with the a_{ij}, i-range, and j-range identical to those in the expressions for A_c and A_s. Pien has found $1 \leq i \leq 5$ and $0 \leq j \leq 3$ to be satisfactory for representing ship-like distribution functions. (ξ^5, for example, can represent a distribution for $0 \leq \xi \leq 1$ quite as well as ξ^6.)

The η surface must be chosen in such a way as to make [4] integrable. For practical purposes this means making η a function of one variable. Using $\eta = \eta(\xi)$,

$$A_c(\theta) = \sum_i \sum_j a_{ij} \frac{K_0 \sec^3\theta}{\pi} \int_\xi \xi^i \cos[b\eta(\xi)] \cos a\xi d\xi \int_\zeta \zeta^j e^{K_0 \zeta \sec^2\theta} d\zeta$$

now with η a function of one variable only, $\int \zeta^j e^{K_0 \zeta \sec^2\theta} d\zeta$ can be analytically integrated. $\int \xi^i \cos[b\eta\ (\xi)] \cos a\xi\ d\xi$ must be integrated numerically. For a catamaran, where $\eta(\xi)$ is equal to a constant, this term could also be evaluated analytically at a great savings in computer time. If this had been done, however, the program's single hull capability would be limited to an Inui representation. For this reason a Gaussian numerical integration is used.

$$\text{Let } Z_j = B \int_{-t}^{0} \zeta^j e^{B\zeta}\ d\zeta$$

with $B = K_o \sec^2\theta$

t = depth of η surface.

$$X_{ic} = \int_{-1}^{1} \xi^i \cos[b\eta(\xi)] \cos a\xi\ d\ \xi$$

$$X_{is} = \int_{-1}^{1} \xi^{i} \cos[b\eta(\xi)] \sin a\xi d\xi$$

$$\therefore\ A_c(\theta) = \frac{\sec\theta}{\pi} \sum_i \sum_j a_{ij} \quad X_{ic} \ Z_j$$

$$A_s(\theta) = \frac{\sec\theta}{\pi} \sum_i \sum_j a_{ij} \quad X_{is} \ Z_j$$

Introduction of Constraints

Recall that $M(\xi,\zeta) = \sum_i \sum_j a_{ij}\ \xi^i \zeta^j$

let $M(\xi,\zeta) = E_1 + E_2 + E_3 + E_4$

where $E_1 = a_{10}\xi + a_{20}\xi^2 + a_{30}\xi^3 + a_{40}\xi^4 + a_{50}\xi^5$

$E_2 = [a_{11}\xi + a_{21}\xi^2 + a_{31}\xi^3 + a_{40}\xi^4 + a_{50}\xi^5]\zeta$

etc.

By Michell thin ship theory

$T = M(1,\zeta)$ $\qquad$ $B = \int M(\xi,\zeta)d\xi$ $\qquad$ $V = \int M(\xi,\zeta)\xi d\xi$ [1.]

where V = nondimensionalized displacement volume.

B = nondimensionalized beam (divided by L)

T = entrance angle.

---

1. $V = \int M(\xi,\zeta)\ \xi d\xi \ = \int \frac{dB(\xi,\zeta)d\xi}{d\xi}$

$$= \int \xi dB(\xi,\zeta) = \xi B - \int \xrightarrow{\ 0\ } \cancel{B(\xi,\zeta)\ d\xi}$$

ξB multiplied by T/L gives gross "nondimensionalized volume."

The constraints place limits on the values of a_{ij}. Any one or a combination of constraints may be used. In the optimization process at least one must be used in order to avoid a zero volume forebody, which of course would have minimum wavemaking resistance.

These constraints will not have the same values as the true hull dimensions because the slope of an actual hull will not be negligible throughout the length as required by thin ship theory. They will of course be closer to the true hull dimensions for a catamaran demihull than for a fuller conventional hull, but will not reflect the hull camber necessary to insure symmetrical flow. In a conversation with the author, Dr. Pien stated that the required camber amounts to one or two degrees, so that neglect of the camber should be adequate for the hull representations used later in this thesis. However, the camber is not neglected in the wave resistance calculations of this thesis.

The Optimization Process

Recall $R_w = \pi \cdot \rho \cdot V^2 \int_0^{\pi/2} ([A_c]^2 + [A_s]^2)\cos^3 \theta d\theta$

find $\dfrac{\partial R_w}{\partial a_{ij}} = 0$ for each value of θ

the result is a five by five matrix multiplied by a_{ij} and equal to zero.

$$\begin{bmatrix} U(1,1) & U(1,2) & U(1,3) & U(1,4) & U(1,5) \\ U(2,1) & & & & \\ U(3,1) & & & & \\ U(4,1) & & & & \\ U(5,1) & & & & \end{bmatrix} \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \\ a_{41} \\ a_{51} \end{bmatrix} = 0$$

considering only E_1, for example.

After introducing one or more constraints,

$$\begin{bmatrix} V(1,1) & V(1,2) & ---- \\ V(2,1) & & \\ \cdot & & \\ \cdot & & \\ \cdot & & \\ \cdot & & \end{bmatrix} \begin{bmatrix} a_{11} \\ a_{21} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} = \begin{bmatrix} B_{11} \\ B_{21} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \end{bmatrix}$$

with [V] a square matrix decreased in dimensions by the number of constraints. After a summation for all θ, the a_{ij}'s are found by a simple matrix inversion.

The Theta Integration

Theta integration involves $\sec^3\theta\ e^{f(\sec^2\theta)}$ in both A_c and A_s. Both oscillate rapidly as θ approaches $\pi/2$. This problem can be handled by making the theta interval smaller and approximately equal to one cycle of A_c or A_s, and by letting 85 degrees rather than 90 degrees be the upper limit of integration. Justification for the cutoff can be made by physical arguments. First, no infinite wave amplitudes have been noted in practice in the $\pi/2$ region. Secondly, the waves that actually exist in the $\theta = \pi/2$ region have very short wave lengths and wave heights and so contribute very little to wave resistance. In the limit of $\theta = \pi/2$, of course, there is no wave disturbance at all.

Application of the Volume Constraint

Only E_1 is independent of depth, and only E_1 determines the waterplane area. The optimization of E_1, therefore, play a major role in minimizing wave resistance. For this reason E_1 should be thought of as being the major contribution to volume, and E_2, E_3 and E_4 used mainly to manipulate the longitudinal centroid of the underwater volume. Suppose the total volume constraint was $V = .35$. One could set the volume constraint for E_1 equal to .30, and that for E_3 equal

to +.05.

Interference Factor

There exists no general agreement on the best way to express the effects of multihull wave interference.

Some researchers (1) have defined an "interference factor", I.F., as follows:

$$I.F. = \frac{R_{RS} - 2DR_{RS}}{2DR_{RS}}$$

where R_{RS} = total catamaran wave resistance

DR_{RS} = demihull wave resistance,

DR_{RS} being equal to the total catamaran wave resistance at infinite separation divided by 2.

This definition is however useful only for the case of symmetrical flow about the demihulls at all hull spacings. To apply it to model tests which embody a fixed hull camber independent of spacing would also not be correct, because the demihull shape should change with spacing as the camber does.

To be able to compare a catamaran design's wave resistance directly with that of a monohull having the same total displacement might seem reasonable. This could be done using linearized wave theory but, as mentioned earlier,

linearized wave theory is likely to give an inflated resistance for a monohull ship. To avoid giving an unwarranted advantage to the catamaran, a separate optimization based either on theory or on model tests should be performed for the monohull.

Furthermore it is not necessarily reasonable to make a comparison between a catamaran and its equivalent monohull. Catamarans can fulfill requirements which monohulls cannot, large deck areas, unusually high transverse stability, or the capability to handle large loads at the center of the ship, for example. It thus makes more sense to compare catamarans of finite spacing to catamarans of infinity spacing as the Turner-Taplin interference factor does.

This thesis therefore employs the Turner-Taplin interference factor with the important exception that DR_{RS} is obtained for a demihull whose wave resistance has been minimized at the condition of infinite spacing. One is thus comparing the wave resistance of an asymmetrical hull which causes a symmetrical wave disturbance at finite spacing with a symmetrical hull which causes an identical wave disturbance at infinite spacing, all under the same constraints.

RESULTS

Results

Figure 1. Interference Factor Plotted Against Froude Number for Three Designs Optimized at Different Froude Numbers. Hull Spacing = .25.

Figure 2. Interference Factor Plotted Against Design Froude Number. Hull Spacing = .25.

Figure 3. Interference Factor Plotted Against Froude Number for a Design Froude Number = .30, and a Number of Hull Spacings.

Figure 4. Interference Factor Plotted Against Hull Spacing Over a Range of Design Froude Numbers.

Figure 5. Design Froude Number Plotted Against Optimum Hull Spacing.

Figures 6a & 6b. Surface Source Distribution for Six Different Design Froude Numbers at Hull Spacing = .25.

Figures 7a & 7b. Non Dimensionalized Ship Half Breadths for Six Different Design Froude Numbers at Hull Spacing = .25.

FIGURE 1

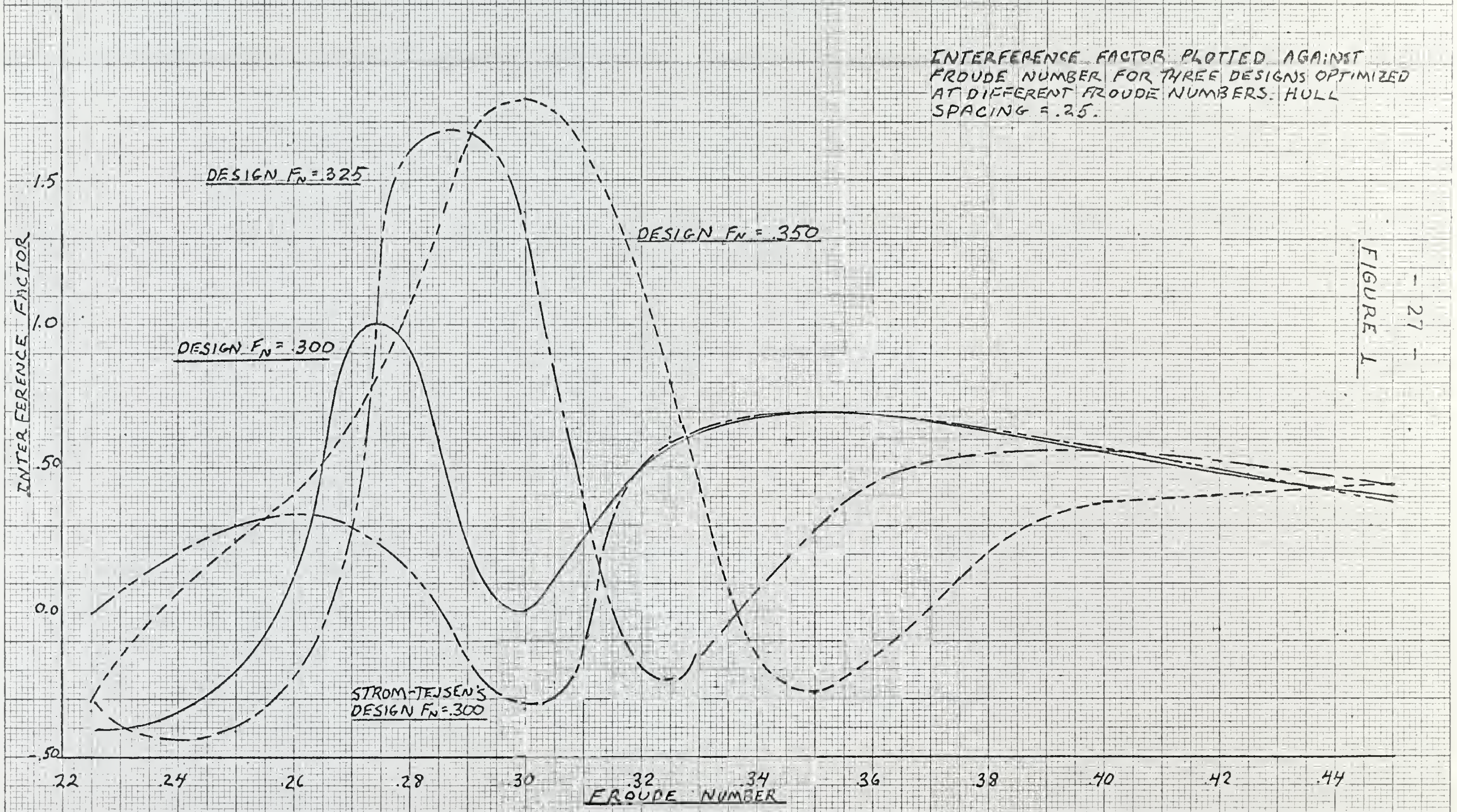
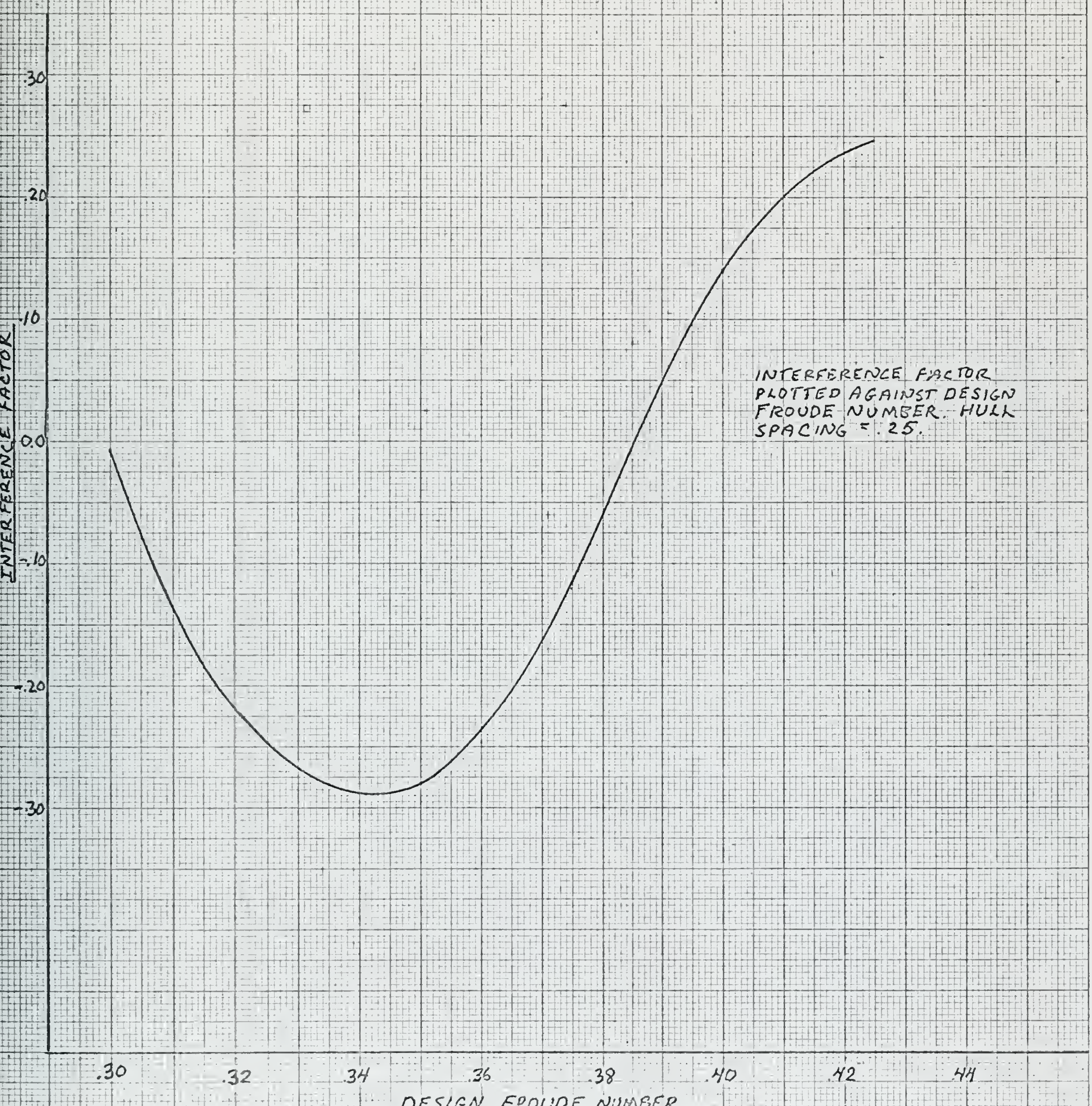
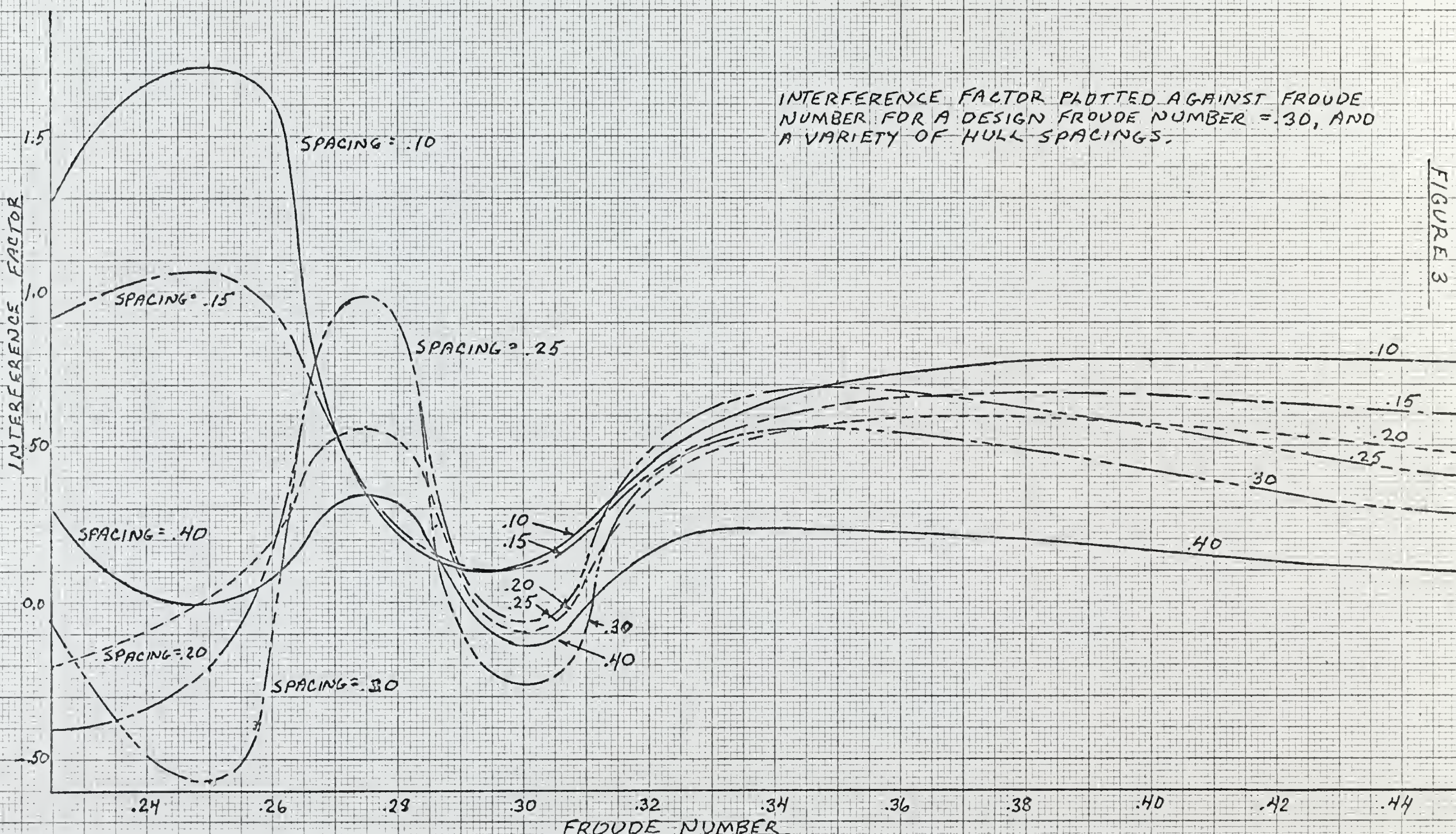

INTERFERENCE FACTOR PLOTTED AGAINST FROUDE NUMBER FOR THREE DESIGNS OPTIMIZED AT DIFFERENT FROUDE NUMBERS. HULL SPACING = .25.
DESIGN F_N = .325
DESIGN F_N = .350
DESIGN F_N = .300
STROM-TEJSEN'S DESIGN F_N = .300
1.5
1.0
.50
0.0
-.50
.22
.24
.26
.28
.30
.32
.34
.36
.38
.40
.42
.44
FROUDE NUMBER
INTERFERENCE FACTOR

FIGURE 2



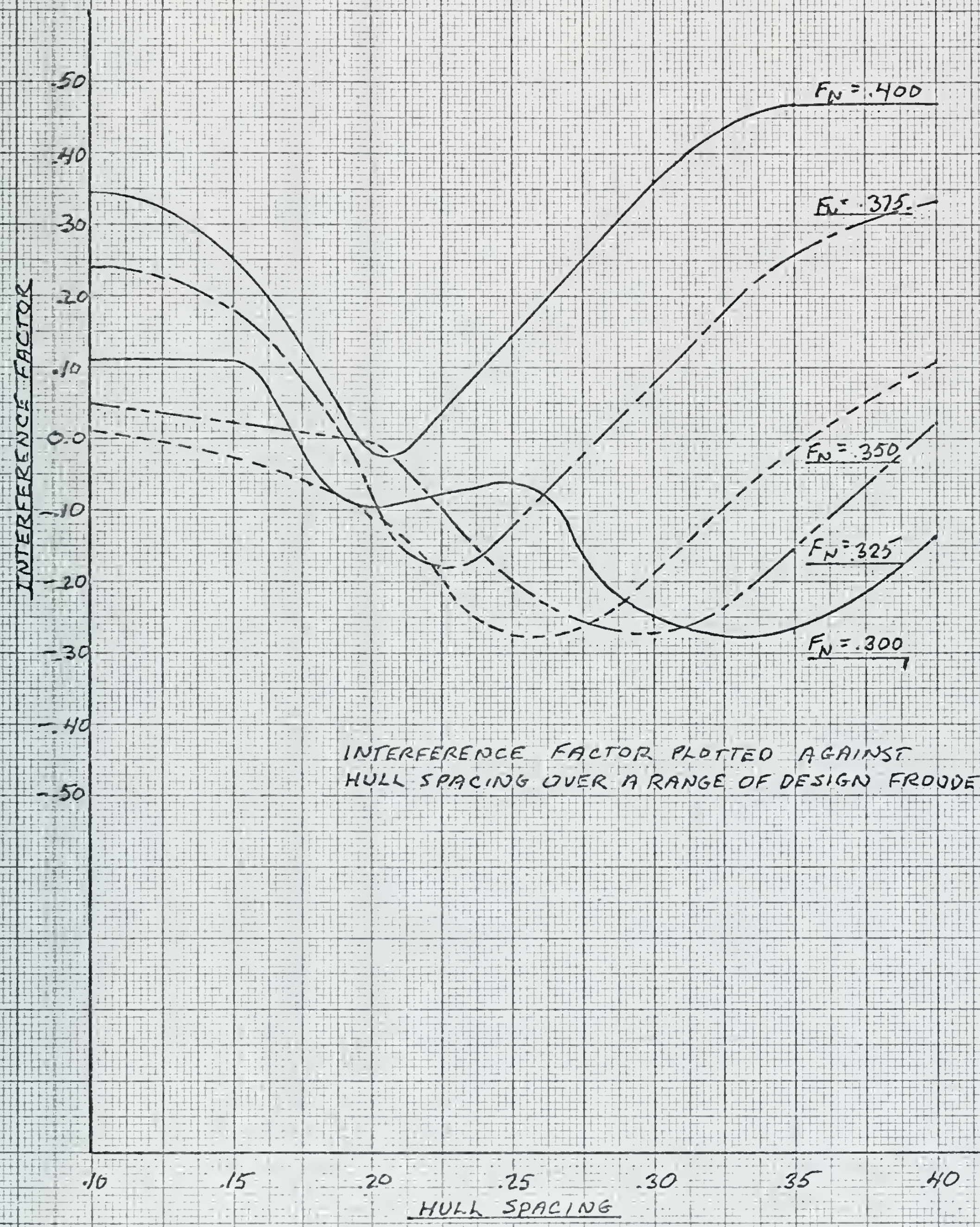
.30
.20
.10
0.0
-.10
-.20
-.30
INTERFERENCE FACTOR
INTERFERENCE FACTOR PLOTTED AGAINST DESIGN FROUDE NUMBER. HULL SPACING = .25.
.30
.32
.34
.36
.38
.40
.42
.44
DESIGN FROUDE NUMBER

FIGURE 3



INTERFERENCE FACTOR PLOTTED AGAINST FROUDE NUMBER FOR A DESIGN FROUDE NUMBER = .30, AND A VARIETY OF HULL SPACINGS.

FIGURE 4.



INTERFERENCE FACTOR PLOTTED AGAINST HULL SPACING OVER A RANGE OF DESIGN FROUDE NUMBERS.

FIGURE 5

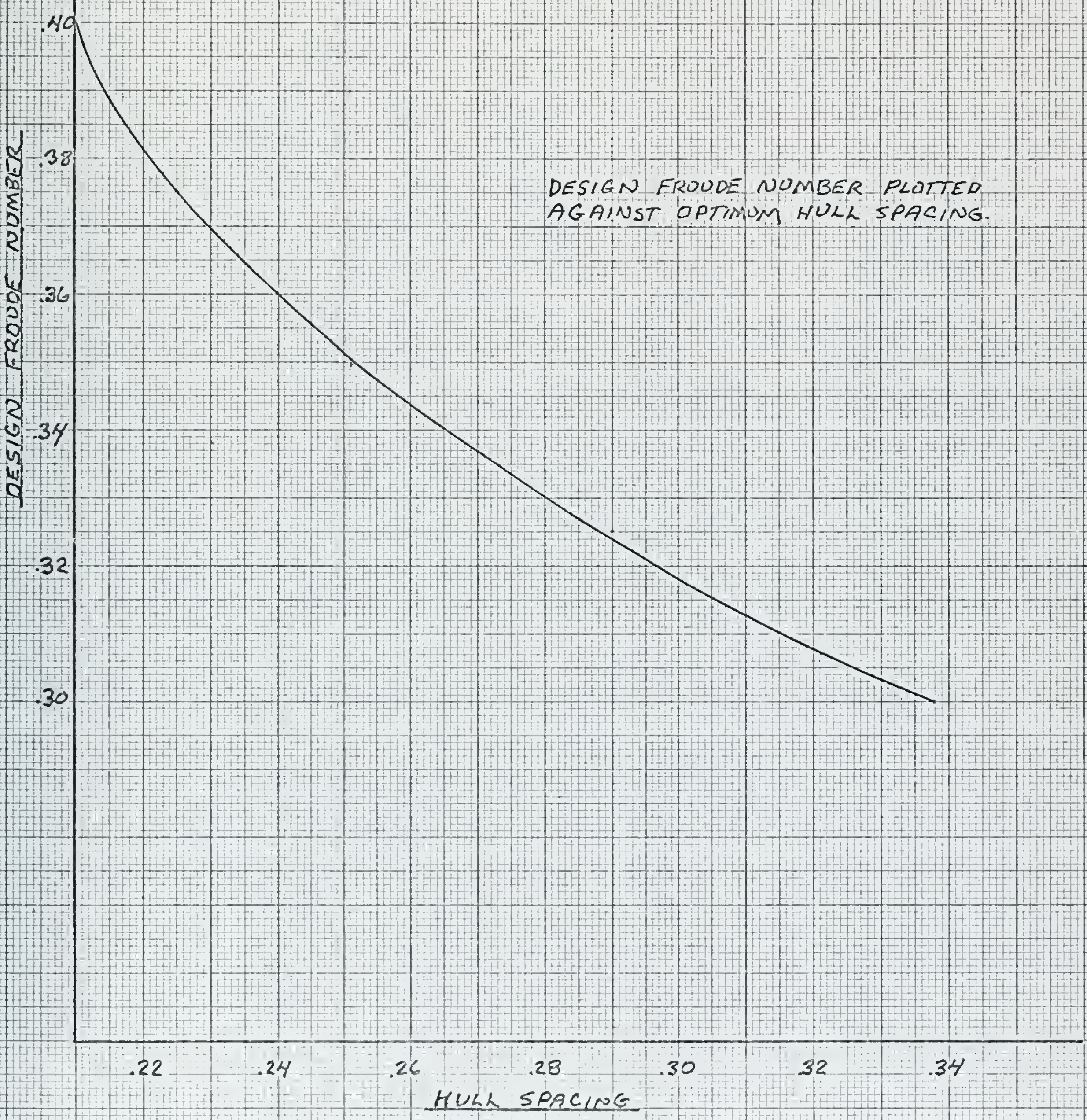

DESIGN FROUDE NUMBER PLOTTED AGAINST OPTIMUM HULL SPACING.
DESIGN FROUDE NUMBER
.40
.38
.36
.34
.32
.30
.22
.24
.26
.28
.30
.32
.34
HULL SPACING

FIGURE 6 a

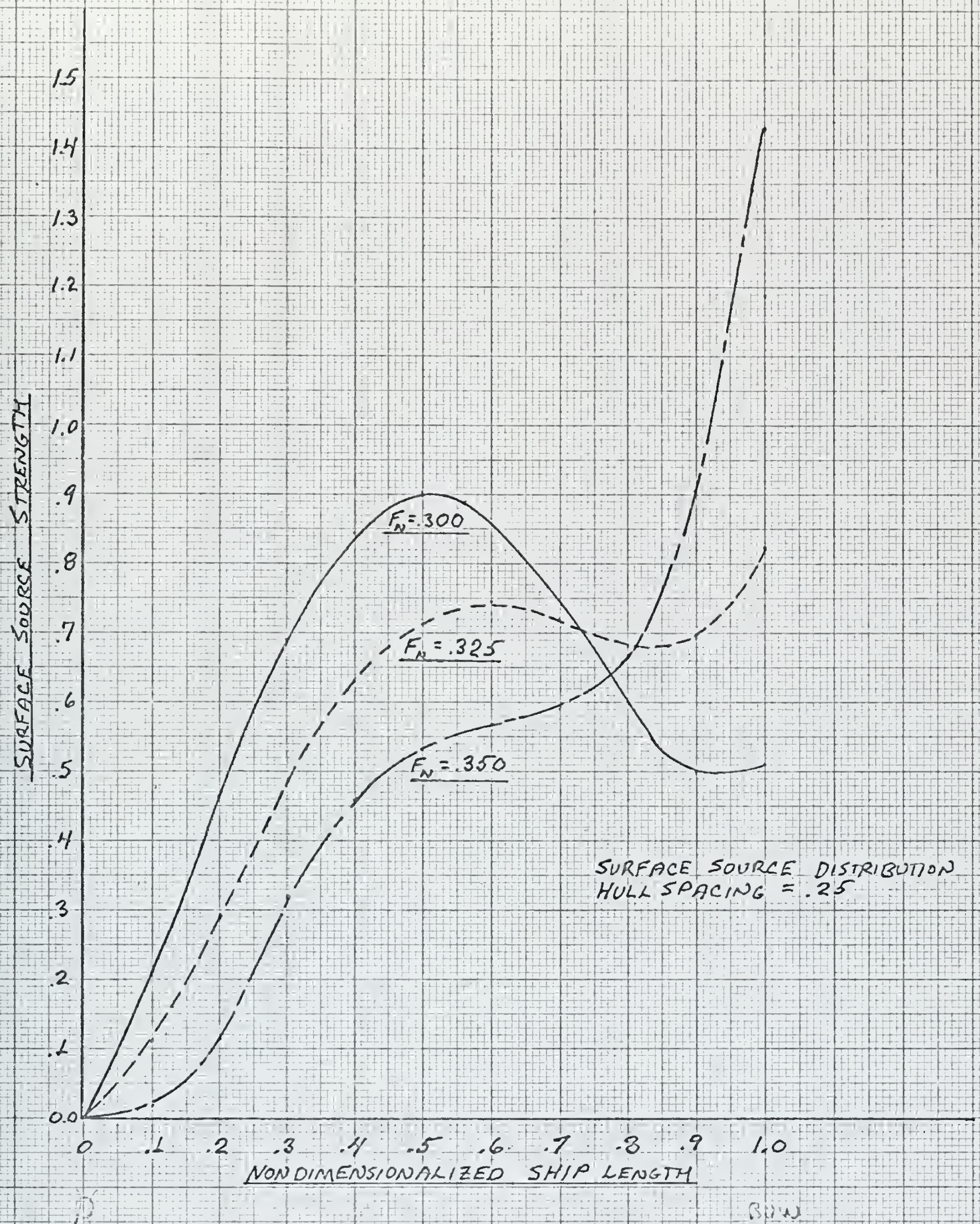

SURFACE SOURCE STRENGTH
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0.0
F_N = .300
F_N = .325
F_N = .350
SURFACE SOURCE DISTRIBUTION
HULL SPACING = .25
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
NONDIMENSIONALIZED SHIP LENGTH
BOW

FIGURE 6 b

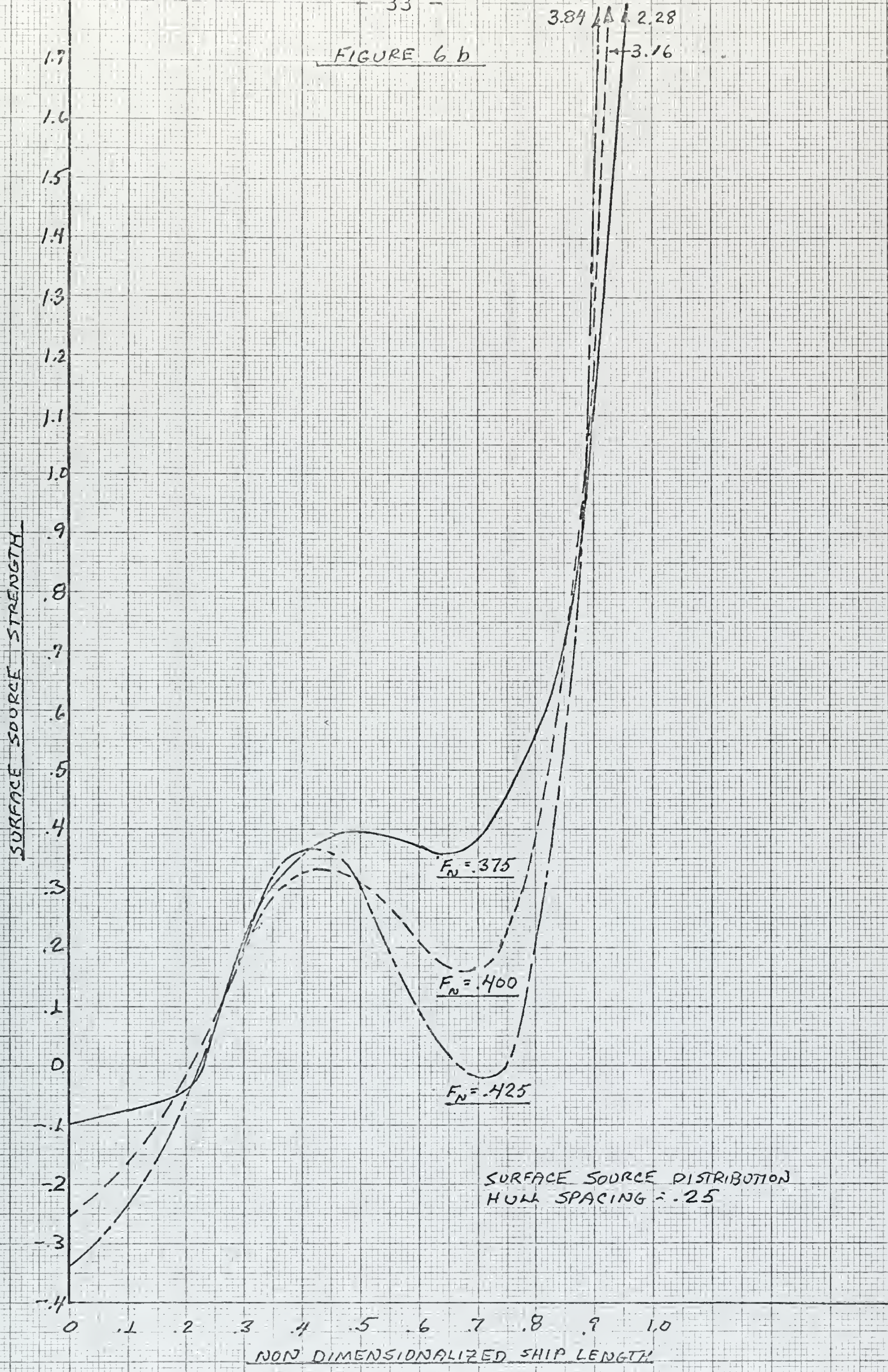

3.84
2.28
3.16
SURFACE SOURCE STRENGTH
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
F_N = .375
F_N = .400
F_N = .425
SURFACE SOURCE DISTRIBUTION
HULL SPACING = .25
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
NON DIMENSIONALIZED SHIP LENGTH

FIGURE 7 a

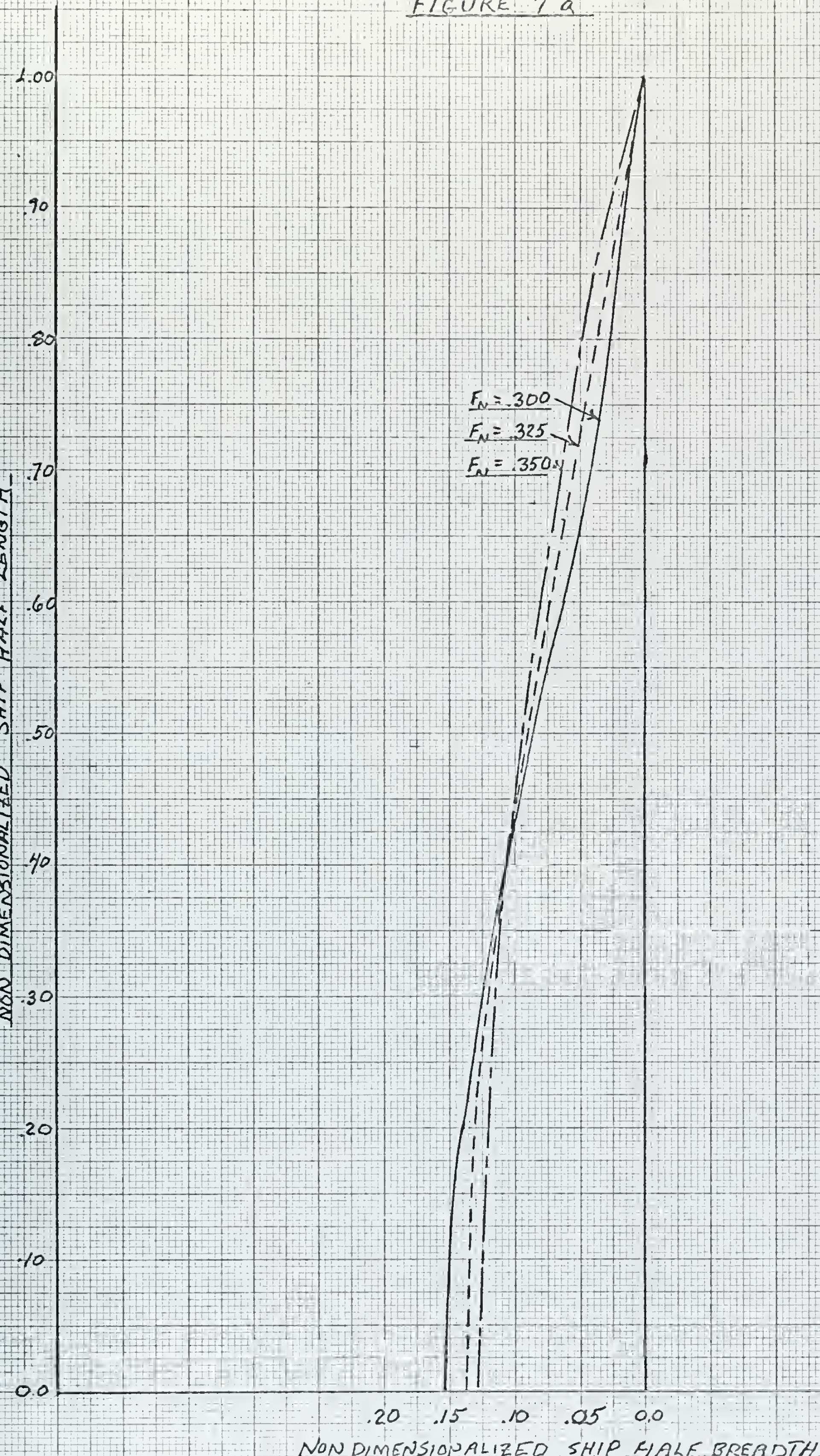
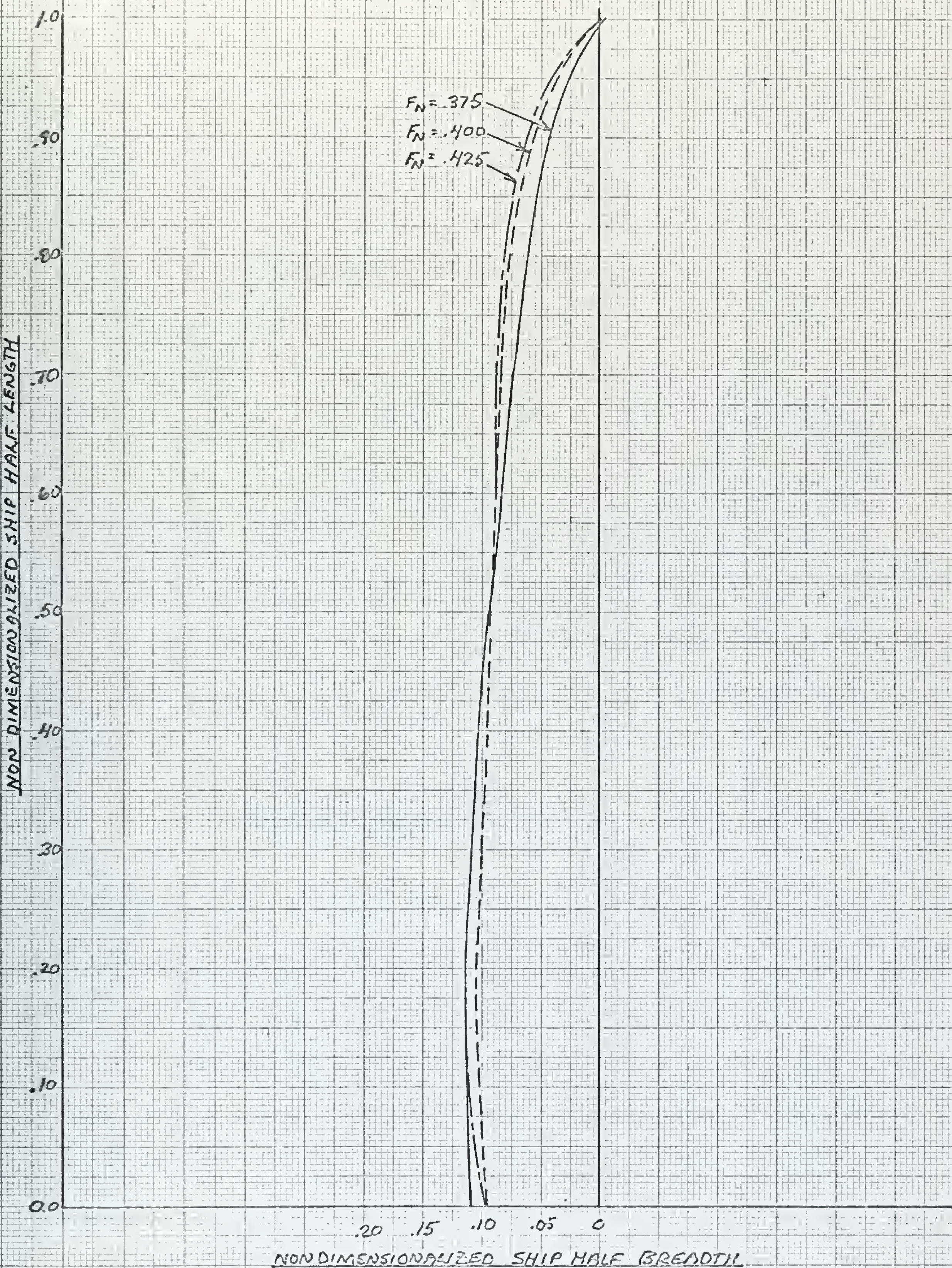

1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0.0
NON DIMENSIONALIZED SHIP HALF LENGTH
$F_N = .300$
$F_N = .325$
$F_N = .350$
.20
.15
.10
.05
0.0
NON DIMENSIONALIZED SHIP HALF BREADTH

FIGURE 7 b



1.0
.90
.80
.70
.60
.50
.40
.30
.20
.10
0.0
NON DIMENSIONALIZED SHIP HALF LENGTH
F_N = .375
F_N = .400
F_N = .425
.20 .15 .10 .05 0
NONDIMENSIONALIZED SHIP HALF BREADTH

DISCUSSION OF RESULTS

Discussion of Results

Program of Validation

The updated and consolidated program was first checked to make sure that the results obtained from it agreed with the results of Pien and Strom-Tejsen's original program. The curve labeled "Strom-Tejsen's Design F_N = .300" in Figure 1 is identical to the one Strom-Tejsen included in his discussion of Reference (1). In addition, a single Eggers calculation for F_N = .325, hull spacing = .20, and surface source strength = El = 1.00 was performed, and compared with Figure 18 of Reference (3). Eggers' value of I.F., approximately .03, compares favorably with the author's value of .018. The author believes, therefore, that the program is completely satisfactory.

Comparison with Experiment

To date no data have been published on catamaran resistance tests in which the demihulls were designed to make symmetrical wave patterns. The work of Everest (9) offers some basis for comparison but even this is not satisfactory. Everest used a parabolic hull form which was not optimized for each Froude number, and varied only the spacing between demihulls and the speed. As will be shown later, the optimum

hull form varies markedly over even a modest change in design Froude number. Model tests based on hull forms determined by this program must be performed before any quantitative comparisons can be made with assurance.

Discussion of Figure 1

This is a plot of Interference Factor (I.F.) against Froude number for three designs optimized at different Froude numbers, at the same hull spacing and displacement volume. It clearly shows, as suggested by Strom-Tejsen in his discussion of Reference (1), that Froude number and hull spacing are not the sole determiners of the I.F. (Turner and Taplin (1) believed that other factors were of secondary importance).

Note that the curve labeled "Strom-Tejsen's Design $F_N = .300$" does not correspond with the author's curve for the same F_N. In order to follow the convention used in (1), Strom-Tejsen compared the wave resistance of the catamaran with demihull design optimized at $F_N = .300$ with that of the identical demihull design at a spacing of infinity. Following Strom-Tejsen's suggestion, the author has compared the wave resistance of a catamaran (with the demihull design optimized as before) with that of a catamaran with the demihull design optimized at an infinite (three demihull half lengths) spacing. While this scheme is certainly sound conceptually, it does cause the catamaran to be somewhat less

attractive from a wave resistance standpoint than the original Strom-Tejsen comparison. Not only is the magnitude of the negative I.F. at the design Froude number reduced, but the magnitude of the positive I.F. at Froude numbers below the design Froude number is greatly increased. Large negative interference factors are predicted in some cases below F_N = .26. At F_N = .26, however, wave interference amounts to only approximately 20% of the total drag according to Everest (9) and therefore is of only secondary interest.

There is, of course, no comparable curve by Everest to Figure 1.

According to Figure 1, the optimum I.F. improves from 0.0 at F_N = .30 to -.23 at F_N = .325, and to -.28 at F_N = .35.

Discussion of Figure 2

In Figure 2, hull spacing was kept constant, and the most favorable I.F. was determined for each of six different design Froude numbers. The range of I.F. is considerable, varying from an I.F. of -.28 at F_N = .34 to an I.F. of +.25 at F_N = .425, and shows how relatively small changes in Froude number can radically affect the magnitude of the most favorable I.F.

Discussion of Figure 3

To obtain Figure 3, the demihull design was optimized at F_N = .30 for six different hull spacings. The results ranged from a positive optimum I.F. of .10 at a spacing of .10 to a negative I.F. of -.26 at a spacing of .30. Everest's Figure 3 in (9) shows some similarities. His optimum spacing, for example, lies between .25 and .30 at an F_N of approximately .33, although of course his hull form was not deliberately optimized there.

Discussion of Figure 4

Figure 4 shows the I.F. plotted against hull spacing for demihulls optimized at five different Froude numbers. To obtain these data it was necessary to run the program over a variety of hull spacing for each design Froude number in order to find the combination of design F_N and hull spacing that yielded the lowest possible I.F. These data are therefore not a cross plot of Figure 3. It appears that demihull forms can achieve significantly negative I.F.'s over a Froude number range from about .30 to about .35 and a corresponding hull spacing range from .25 to .325. At the best hull spacing, an I.F. of approximately -.28 can be reached at these Froude numbers.

Discussion of Figure 5

Figure 5 is merely an envelope plot of the optimum hull spacings obtained from Figure 4. It shows a decreasing optimum hull spacing with increasing design Froude number. Everest's Figure 2iii (9) shows the same trend which he later verified experimentally.

Discussion of Figure 6

Figures 6a and 6b are plots of one of the program outputs, namely the surface source distribution for demihull forms optimized at six different Froude numbers. The most noticeable trend is the rapid increase in source strength at the bow and rapid decrease in source strength in the midships area. For a constant volume body this represents a transfer of volume from amidships to the bow area.

Discussion of Figure 7

Figures 7a and 7b are the approximate Michell thin ship theory representations of the hull forms given by the surface source distributions plotted in Figures 6a and 6b. They are only approximate representations because as discussed earlier, the small asymmetry of the demihull necessary to ensure wave symmetry is ignored. They do represent the first step in the

stream line plotting necessary to produce the asymmetric demi-hulls required for symmetric flow, however. And they show very well the redistribution of volume that takes place with increasing Froude number. There can be no doubt that the demihull form has a decisive influence on catamaran wave resistance. Note the flow of volume forward into an even more bulbous bow, and the decrease in beam as Froude number increases.

The study optimized only E1, therefore this is a wall sided form. If E1 in conjunction with any combination of E2, E3, and E4 were used, a non wall sided form could be obtained and the half breadths at waterplanes below the water line could be calculated.

General Discussion

1. The high positive I.F.'s for Froude numbers below the design Froude number do present the catamaran designer with a serious problem. Consider, for example, Figure 1 for the demihull optimized at $F_N = .35$. The largest negative I.F. occurs at $F_N = .35$, and equals -.28, while the largest positive I.F. occurs at $F_N = .30$ and equals 1.78. A simple calculation indicates the magnitude of the problem:

$$\frac{F_{N1}}{F_{N2}} = \frac{V_1}{V_2} = \frac{.35}{.30} = \frac{7}{6} \quad \text{where V = ship speed}$$

$$I.F._1 = \frac{C_1 - C_\infty}{C_\infty} = -.28 \qquad C_1 = .72\ C_\infty$$

$$I.F._2 = \frac{C_2 - C_\infty}{C_\infty} \qquad C_2 = 2.78\ C_\infty$$

$$\frac{R_1}{R_2} = \frac{C_1}{C_2}\left(\frac{V_1}{V_2}\right)^2 = \frac{.72}{2.78}\left(\frac{7}{6}\right)^2 = .35$$

Wavemaking resistance thus decreases three fold over a 14% increase in Froude number.

This problem can be attacked in two ways. First, by limiting design Froude numbers to the low end of the range where positive (and negative!) I.F.'s are lower. Or secondly, by optimizing at two different Froude numbers at once, that is, possibly sacrificing some of the negative I.F. at $F_N = .35$ to gain a reduction in the positive I.F. at $F_N = .30$. Strom-Tejsen has done this in unpublished work at N.S.R.D.C. It may be hard to do this without sacrificing a great deal of the negative I.F., however. Note from Figure 1 that a demi-hull design optimized for $F_N = .30$ has a positive I.F. at $F_N = .28$ almost as great as that for $F_N = .35$. Hence a

design optimized at both $F_N = .30$ and $F_N = .35$ would probably gain little in the reduction of positive I.F. More work needs to be done in this area.

2. From a practical standpoint, the cost and weight of the structure connecting the two demihulls will pressure the designer to go to the smallest demihull separation feasible. These are efficient only at high Froude numbers, which can be obtained only by increasing design speed (since to decrease ship length would only increase the nondimensionalized demihull spacing.) This fact places a premium on model testing, sincd it is certainly true that viscous effects increase with ship speed, and viscous effects are not taken into account theoretically. In addition, one has the unfortunate increase in the positive I.F. with increasing Froude number to contend with.

3. For small catamaran ships it may be practicable to devise a scheme for changing demihull spacing with Froude number, thus avoiding the large positive I.F. "hump" below the design Froude number. Of course, the hull form would not be optimized at the lower Froude numbers, but if a designer were particularly clever, it should be possible - again, for a small catamaran - to change the waterline demihull form by allowing the demihulls to rotate as the spacing changes.

4. Eventually a model testing program must be undertaken both to check the results predicted by theory and to determine the importance of viscous effects as the hull spacing changes.

CONCLUSIONS

Conclusions

1. The extensive updating and consolidation of the original program of Pien and Strom-Tejsen has been successful.

2. The maximum cancellation of diverging waves requires symmetric wave patterns, which in turn requires symmetric demihulls.

3. "Interference Factor" is most usefully defined as the ratio of the difference between the resistances of a catamaran optimized at a certain speed and spacing and a catamaran with the same displacement optimized at the same speed and a spacing of infinity, to the resistance of the latter.

4. Small changes in design (outside of the range $.32 < F_n < .36$) can radically alter the magnitude of I.F. at constant demihull spacing.

5. Optimum demihull spacing decreases with increasing Froude number.

6. For a demihull with the constraints used in this study, the most favorable interference factors are found at Froude numbers between .30 and .35, and corresponding hull spacings ranging from .20 to .34. A most favorable I.F. of -.28 was obtained in this domain.

7. Unfavorable I.F.'s at Froude number slightly below the design Froude number will present powering problems to the designer. In one case the wavemaking resistance at the lower Froude number was three times that at the design Froude number.

8. Unknown effects of viscosity, wave reflection and breaking between demihulls, and the necessity to check the theoretical results make model testing relatively indispensable.

9. Reduction of wavemaking resistance by favorable wave interference between demihulls is unlikely to make dramatic reductions in total ship resistance. The catamaran does, however, have a much better slenderness ratio for the same length and displacement than does a monohull, with a corresponding decrease in wavemaking resistance which may be considerable.

10. Demihull form has as decisive an influence on wavemaking resistance as Froude number and hull spacing.

RECOMMENDATIONS

Recommendations

1. More studies involving the optimization of combinations of E2, E3, and E4 together with E1, line sources and doublets, and point sources and doublets should be undertaken. At present, the impact of changes in one or more of these factors on demihull form and catamaran wavemaking resistance cannot be predicted. Since wavemaking resistance is to a great extent a function of the shape of the waterline, changes in E2, E3, and E4 are not likely to affect resistance appreciably. This is not true, of course, of the bulbous appendices represented by line and point singularities. In addition, the latter may be used to reduce the entrance angle of the main hull form in order to minimize spray.

2. The effect of simultaneous optimization at the design Froude number and at the Froude number where the unfavorable interference factor would otherwise be highest upon the most favorable interference factor should be determined.

3. A streamline tracing program should be developed to facilitate the rapid development of asymmetric demihull forms, using as input the singularity distribution which is the output of the author's program.

4. Model testing to check the theoretical results and to investigate the effects of viscosity, and wave reflection and wave breaking between demihulls should be undertaken. Model testing could take two forms:

a) Single demihull tests such as those performed by Everest (9) in which the wave patterns are measured experimentally and then combined by a computer program. The advantages of this approach are that relatively large demihulls can be tested in a small tow tank, and the symmetrical models are less expensive to construct. The disadvantages are that the effects of wave breaking and reflection between demihulls cannot be determined.

b) Conventional tow tank testing of a complete catamaran with asymmetric demihulls. This approach has the advantage of being most direct, and includes the effects of wave breaking and reflection between demihulls. It has the disadvantages of requiring twice as many demihull models, the models must be asymmetric and more expensive to build, and the size of the model which may be tested without towing tank wall effect interference is smaller than that for method (a).

APPENDIX

Specification for Integration with Respect to ξ

Integration in the X direction is carried out by breaking the total interval into subintervals and using the Gaussian integration formula in each subinterval.

The subinterval length is defined by the NGS value, and the number of Gaussian stations in each subinterval is given by NG. NG = 10, NGS = 10 are recommended.

NG =	
NGS =	

FORMAT(918)

ABSCISSA VALUES		WEIGHT FACTORS	
G(1,1) =		G(2,1) =	
G(1,2) =		G(2,2) =	
G(1,3) =		G(2,3) =	
G(1,4) =		G(2,4) =	
G(1,5) =		G(2,5) =	
G(1,6) =		G(2,6) =	
G(1,7) =		G(2,7) =	
G(1,8) =		G(2,8) =	
G(1,9) =		G(2,9) =	
G(1,10) =		G(2,10) =	
G(1,11) =		G(2,11) =	
G(1,12) =		G(2,12) =	
G(1,13) =		G(2,13) =	
G(1,14) =		G(2,14) =	
G(1,15) =		G(2,15) =	

FORMAT (6F12.8)

FORMAT (6F12.8)

The abscissae values and the weight factors used in the Gaussian formula should be stated in the columns above. Check that the number of stations correspond to the NG value stated above.

SPECIFICATION FOR INTEGRATION ACCURACY

Integration accuracy can be specified by giving the θ values at which the integration interval should be halved. The following θ values are suggested. .8729, 1.2217, 1.3090, 1.3963, 1.4813 (50°, 70°, 75°, 80°, 85°) EI(9) = DX used in the integration. DX = .30 is recommended.

EI(1) = ________

EI(2) = ________

EI(3) = ________

EI(4) = ________

EI(5) = ________

EI(6) = ________

EI(7) = ________

EI(8) = ________

EI(9) = ________

FORMAT (9F8.5)

SPECIFICATION OF TITLE

Title is an identification and page shifting device used in the printing out of data. It can be anything that takes up less than 72 spaces. Format (18A4).

SPECIFICATION OF GEOMETRY

DEN: End of integration in X direction. If the hull is symmetrical, or if only the forebody calculation is required, DEN = 0.

ARP: This gives the origin for the weighted free wave amplitudes (both sine and cosine). If one wished to see what effect a certain line source and/or line doublet (bulbous bow) distribution had on the wave amplitude, setting ARP = 1 would put the origin of the amplitude printout at the bow. Thus the effect of the line source and/or line doublet distribution would not be masked by the surface source distribution. The printout is for design Froude number.

PC(1): Forebody demihull hull spacing, measured at the bow, and is the half distance between hulls divided by the length of the forebody. (centerplane to centerplane)

PC(2): Afterbody demihull hull spacing. Measured at the stern. Half distance between hulls divided by forebody length. (centerplane to centerplane)

DEN =		FORMAT(9F8.5)
ARP =		
PC(1) =		
PC(2) =		

SPECIFICATION FOR LOGIC

NXM: If NXM = 0, no surface source distribution is to be read in. If NXM ≠ 0, surface source distribution is to be read in.

NDS: If NDS = 0, no line source or line doublet distribution is to be read in. If NXM ≠ 0, the distribution is to be read in.

NBD: Number of restraints when optimizing hull form.

NBD = 0 no restraints. This is a necessary condition for distributions to be read in, rather than optimized.

NBD = 1 Displacement volume is chosen as restraint.

NBD = 2 Volume and beam are chosen.

NBD = 3 Volume, beam, and entrance angle are chosen.

NP: Equivalent to N in the ETA surface equation.

NP = 2 has been found satisfactory.

NTEST: If NTEST = 0, calculation will end after running through one set of data. If NTEST > 0, calculation will continue to another data set following the first.

NXM	= NMK(I,1)	
NDS	= NMK(I,2)	
	NMK(I,3)	
	NMK(I,4)	
NBD	= NMK(I,5)	
NP	= NMK(I,6)	
	NMK(I,7)	
NTEST	= NMK(I,8)	
	NMK(I,9)	

GEOMETRIC AND SPEED INPUTS

BM : Beam in eta eq'n

AC : "a" value in eta eq'n

BC : "-t" = draft of eta surface

DDF: Theta increment. .0349 rad. recommended

DDE: Upper integration limit. 1.4813 rad.

F1 : Froude number for lowest speed value

FD : Froude number increment

F2 : Froude number for highest speed value

FDN: Design Froude number

CM : Cosine multiplier

PT : Weighted wave amplitudes printed if PT $\neq$ 0

TSD: Multiplier if line source/doublet present

TB : Depth of line source, line doublet

BM	= CMK(1,1) =	
AC	= CMK(1,2) =	
BC	= CMK(1,3) =	
T	= CMK(1,4) =	
DDF	= CMK(1,5) =	
DDE	= CMK(1,6) =	
F1	= CMK(1,7) =	
FD	= CMK(1,8) =	
F2	= CMK(1,9) =	
FDN	= CMK(1,10) =	
CM	= CMK(1,11) =	
SM	= CMK(1,12) =	
PT	= CMK(1,13) =	
	CMK(1,14) =	
TSD	= CMK(1,15) =	
	CMK(1,16) =	
	CMK(1,17) =	
TB	= CMK(1,18) =	

FORMAT(9F8.5)

NOTES

CM : The cosine component of both diverging and

SM : Transverse waves are cancelled for a symmetrical ship. In this case CM = 0, and SM = 2.

TSD: Multiplier if line source/doublet present. If at bow alone, TSD = 1. If at bow and stern of symmetrical ship, TSD = 2. If not symmetrical, value determined by degree of phase shift between bow and stern sources and/or doublets.

TB : A value must be entered to avoid computer erroneously exceeding variable size limits - even if line source/ doublet not used. TB approximately equal to T is adequate.

LINE SOURCE AND LINE DOUBLET DISTRIBUTION

TO BE SPECIFIED IF NDS $\neq$ 0

E_9

S(I,1) =		FORMAT(5F14.8)
S(I,2) =		
S(I,3) =		
S(I,4) =		
S(I,5) =		

D(I,1) =		FORMAT(5F14.8)
D(I,2) =		
D(I,3) =		
D(I,4) =		
D(I,5) =		

$$E_9 = S(I,1)\zeta + S(I,2) + S(I,3)\zeta^2 + S(I,4)\zeta^3$$

$$E_{10} = D(I,1) + D(I,2)\zeta + D(I,3)\zeta^2 + D(I,4)\zeta^3$$

S(I,5) = point source

D(I,5) = point doublet

Cosine and sine multiplier valid for line source and line doublet distribution

		Symmetric	Bow Alone
cosine multiplier	CCB	0	1
sine "	SSB	2	1

FBP(1) forebody location of line source

BPC(1) forebody location of line doublet

CCB(I) =		FORMAT(9F8.5)
SSB(I) =		
FBP(I) =		
BPC(I) =		

RESTRAINTS ON E_1, E_2, E_3 and E_4

SPECIFIED IF NXM = 0

VOLUME		BEAM		T	
ZE(1,1) =	FORMAT(9F8.5)	ZE(2,1) =	FORMAT(9F8.5)	ZE(3,1) =	FORMAT(9F8.5)
ZE(1,2) =		ZE(2,2) =		ZE(3,2) =	
ZE(1,3) =		ZE(2,3) =		ZE(3,3) =	
ZE(1,4) =		ZE(2,4) =		ZE(4,4) =	

No restraints can be used when optimizing E_9 and E_{10}. Nevertheless the ZE values should be filled out according to the NBD value.

SPECIFY PRIORITY IN OPTIMIZATION

KR1: Optimize using "displacement volume" as restraint

KR2: Optimize using beam as restraint

KR3: Optimize using entrance angle as restraint

Example

NBD = Number of restraints = 2

KR1 = 1, KR2 = 3, KR3 = 2.

Then "volume" and entrance angle will be used in optimization.

KR1 =	FORMAT(9I8)
KR2 =	
KR3 =	

SPECIFICATION FOR OPTIMIZATION SCHEME

IL(1) $\neq$ 0 E_1 should be optimized

IL(2) $\neq$ 0 E_2 " " "

IL(3) $\neq$ 0 E_3 " " "

IL(4) $\neq$ 0 E_4 " " "

IL(5) $\neq$ 0 E_9 " " "

IL(6) $\neq$ 0 E_{10} " " "

IL(1) =	
IL(2) =	
IL(3) =	
IL(4) =	
IL(5) =	
IL(6) =	
IL(7) =	

FORMAT(9I8)

The last IL value should be put = 0 indicating no more E values are to be optimized.

SPECIFY NUMBER OF TERMS IN E_1, E_2, ETC.

If KN(1) = 4, then E_1 contains four terms

I.E. $E_1 = a_{11}\ \xi + a_{21}\ \xi^2 + a_{31}\ \xi^3 + a_{41}\ \xi^4$

KN(1) =	
KN(2) =	
KN(3) =	
KN(4) =	

FORMAT(9I8)

SPECIFY SURFACE SOURCE DISTRIBUTION

TO BE READ IN IF NXM ≠ 0

Surface Source Distribution $M(\xi,\zeta) = \sum_{i=1}^{4} \sum_{j=1}^{5} XM_{i,j}\ \zeta^{(i-1)} \xi^{j} =$

$$E_1 + E_2\ \zeta + E_3\zeta^2 + E_4\zeta^3$$

E_1			E_2		
XMBB(1,1) =		FORMAT(5F14.8)	XMBB(2,1) =		FORMAT(5F14.8)
XMBB(1,2) =			XMBB(2,2) =		
XMBB(1,3) =			XMBB(2,3) =		
XMBB(1,4) =			XMBB(2,4) =		
XMBB(1,5) =			XMBB(2,5) =		

E_3			E_4		
XMBB(3,1) =		FORMAT(5F14.8)	XMBB(4,1) =		FORMAT(5F14.8)
XMBB(3,2) =			XMBB(4,2) =		
XMBB(3,3) =			XMBB(4,3) =		
XMBB(3,4) =			XMBB(4,4) =		
XMBB(3,5) =			XMBB(4,5) =		

APPENDIX B

```
C     PROGRAM FOR COMPUTATION OF WAVE RESISTANCE.  ADAPTED FROM A
C     PROGRAM WRITTEN BY DR. PAO C. PIEN AND DR. STROM-TEJSEN, NSRDC.
C
      DIMENSION G(2,15),S(2,9),D(2,9),ZE(6,9),XMBB(6,9),CSR(20,20),
     XACB(250),ACC(250),ASS(250),ASSS(250),ACSS(250),ASLS(250),ACLS(250)
     X,ASLD(250),ACTH(250,6),ASTH(250,6),Z(2,7),ZB(2,7),CCB(2),SSB(2),
     XFBP(2),ECS(2),ECD(2),TDS(2),ACLD(250),CSL(20,20),CL(20,20)
     X,WRCT(50),FKF(50),DFF(250),EI(9),CCL(20,20),DBT(2),PC(2),BPC(2),
     XCCR(20,20),XZ(15,10),SXB(15),DXB(15),THDN(250),IL(20),KN(20),
     XXMSS(6,9),WRCFB(50),WRCTS(50),NMK(2,9),CMK(2,18),TITLE(18),
     XBB(15,10)
      DATAF(GQ)=BM*(-3.*EN*(1.-AC-BC)*QQ**(3*NP-1)-2.*EN*BC*QQ**(2*NP-1
     X)-EN*AC*QQ**(NP-1))
C
C     READ IN VALUES AND INITIALIZE
C
      READ (5,3) NG,NGS
   22 READ (5,7) ((G(I,J),J=1,NG),I=1,2)
      READ (5,2) (EI(J),J=1,9)
      READ (5,1) TITLE
      WRITE(6,6) TITLE
  311 DO 150 I=1,2
      DO 151 J=1,9
      S(I,J)=0.
      D(I,J)=0.
  151 CONTINUE
  150 CONTINUE
      DO 152 I=1,4
      DO 153 J=1,5
      XMBB(I,J)=0.
      XMSS(I,J)=0.
  153 CONTINUE
  152 CONTINUE
      CCB(1)=0.
      CCB(2)=0.
      SSB(1)=0.
```

```
      SSB(2)=0.
      FBP(1)=0.
      FBP(2)=0.
      BPC(1)=0.
      BPC(2)=0.
      READ (5,2) DEN,ARP,PC(1),PC(2)
      WRITE(6,2) DEN,ARP,PC(1),PC(2)
    1 FORMAT(18A4)
    6 FORMAT(1H1,18A4)
 9112 READ (5,3) (NMK(1,J),J=1,9)
C     NXM,NDS,NBD,NP,NTEST
      WRITE(6,3) (NMK(1,J), J=1,9)
      NDS=NMK(1,2)
      NBD=NMK(1,5)
      CBT(1)=1.
      DBT(2)=-1.
      READ (5,2) (CMK(1,J),J=1,18)
C     BM,AC,BC,T,DDF,DDE,F1,FD,F2,FDN,CM,SM,PT,TSD,TB
      WRITE(6,2) (CMK(1,J),J=1,18)
      FDN=CMK(1,10)
      BM=CMK(1,1)
C
C     TEST TO SEE IF FOREBODY LINE SOURCE AND LINE DOUBLET DATA ARE TO
C     BE READ IN
C
      IF(NMK(1,2))101,100,101
  101 READ (5,5) (S(1,J),J=1,6)
      READ (5,5) (D(1,J),J=1,6)
      WRITE(6,5) (S(1,J),J=1,6)
      WRITE(6,5) (D(1,J),J=1,6)
      READ  (5,2) CCB(1),SSB(1),FBP(1),BPC(1)
      WRITE (6,2) CCB(1),SSB(1),FBP(1),BPC(1)
C
C     TEST TO SEE IF CONSTRAINTS ARE TO BE READ IN
C
  100 IF(NMK(1,5))102,103,102
```

```
  102 DO 432 J=1,NBD                                                    XPXP
  432 READ (5,2) (ZE(J,L),L=1,8)
      DO 710 J=1,NBD
  710 WRITE(6,2) (ZE(J,L),L=1,8)
      READ (5,3) KR1,KR2,KR3
      READ (5,3) (IL(J),J=1,9)
      READ (5,3) (KN(J),J=1,8)
      WRITE(6,3) KR1,KR2,KR3
      WRITE(6,3) (IL(J),J=1,9)
      WRITE(6,3) (KN(J),J=1,8)
      M=1
C
C     INSERTION OF CONSTRAINTS
C
  271 DO 400 K=1,5
      CL(KR1,K)=1./FLOAT(K+2)
      CL(KR2,K)=1./FLOAT(K+1)
      CL(KR3,K)=1.
  400 CONTINUE                                                          XPXP
  511 N6=NBD                                                            XPXP
C
C     TEST TO SEE IF FOREBODY SURFACE SOURCE DATA IS TO BE READ IN
C
  103 IF(NMK(1,1))104,114,104
  104 READ (5,5) ((XMBB(I,J),J=1,5),I=1,4)
      WRITE(6,5) ((XMBB(I,J),J=1,5),I=1,4)
  114 FGS=FLOAT(NGS)
      NMK(2,2)=0.
C
C     TEST TO SEE IF AFTERBODY DATA SHOULD BE READ IN
C
      IF(DEN)820,821,821
  820 WRITE(6,822)
  822 FORMAT (21H AFTERBODY INPUT DATA)
      READ (5,3) (NMK(2,J),J=1,9)
      WRITE(6,3) (NMK(2,J),J=1,9)
```

```
      READ (5,2) (CMK(2,J),J=1,18)
      WRITE(6,2) (CMK(2,J),J=1,18)
C
C     TEST TO SEE IF AFTERBODY LINE SOURCE AND LINE DOUBLET DATA ARE TO
C     BE READ IN
C
      IF(NMK(2,2))823,824,823
  823 READ (5,5) (S(2,J),J=1,6)
      READ (5,5) (D(2,J),J=1,6)
      WRITE(6,5) (S(2,J),J=1,6)
      WRITE(6,5) (D(2,J),J=1,6)
      READ (5,2) CCB(2),SSB(2),FBP(2),BPC(2)
      WRITE(6,2) CCB(2),SSB(2),FBP(2),BPC(2)
C
C     TEST TO SEE IF AFTERBODY SURFACE SOURCE DATA ARE TO BE READ IN
C
  824 IF(NMK(2,1))825,821,825
  825 READ (5,5) ((XMSS(I,J),J=1,5),I=1,4)
      WRITE(6,5) ((XMSS(I,J),J=1,5),I=1,4)
  821 CONTINUE
C
C     INSERTION OF FOREBODY AND AFTERBODY LENGTHS
C
      TDS(1)=1.
      TDS(2)= DEN
      T=CMK(1,4)
      MF=1                                                              XPXP0026
      KF=1                                                              XPXP0038
  111 F= CMK(1,7)
C
C     IF DISTRIBUTION IS TO BE OPTIMIZED, FROUDE NUMBER IS SET EQUAL
C     TO THE DESIGN VALUE.  START OPTIMIZATION OF E-COMPONENT.
C
      IF(NBD .GT. 0) F=CMK(1,10)
  110 N5=KN(M)-NBD
      IF(NBD .EQ. 0) GO TO 8
```

```
      DO 154 I=1,20
      DO 155 J=1,20
      CCR(I,J)=0.
  155 CONTINUE
  154 CONTINUE
C
C     GENERATE MATRICES FOR COEFFICIENT SOLUTION.
C
      DO 405 J=1,NBD                                              XPXP
      DO 404 K=1,NBD                                              XPXP
  404 CCL(J,K)=CL(J,K)                                            XPXP
      DO 405 K=1,N5                                               XPXP
      KL=K+NBD                                                    XPXP
  405 CCR(J,K)=-CL(J,KL)                                          XPXP
      CCR(1,N5+1)=1.                                              XPXP
      CCR(2,N5+2)=1.                                              XPXP
      CCR(3,N5+3)=1.                                              XPXP
      IF(NBD-1)1415,1415,413
  413 CALL TEJSEN (CCL,NBD,CCR,5,Q,ID)
      GO TO (8,9),ID                                              XPXP
 1415 DO 1416 K=1,5
 1416 CCR(1,K)=CCR(1,K)/CL(1,1)
C
C     INDICATES WHICH ELEMENT IS OPTIMIZED.
C
    8 CONTINUE
      LI=IL(M)
      LJ=LI
      LIJ=LJ-4
      IF(LIJ .LE. 0) GO TO 21
   20 LI=LIJ
   21 DO 156 I=1,20
      CSR(I,1)=0.
  156 CONTINUE
      DO 157 I=1,6
      DO 158 J=1,6
```

```
      CSL(I,J)=0.
  158 CONTINUE
  157 CONTINUE
C
C     CALCULATION STARTING POINT FOR EACH NEW FROUDE NUMBER.
C
  805 R=.5/(F*F)
      DO 159 I=1,250
      ASSS(I)=0.
      ACSS(I)=0.
      ASLS(I)=0.
      ACLS(I)=0.
      ASLD(I)=0.
      ACLD(I)=0.
      DO 160 J=1,6
      ASTH(I,J)=0.
      ACTH(I,J)=0.
  160 CONTINUE
  159 CONTINUE
      WR=0.
      WRF=0.
      WRS=0.
      CCSR=0.
C
C     INITIAL THETA AND DELTA THETA VALUE.
C
      DFD=CMK(1,5)
      DN=DFD/2.
C
C     IE COUNTS SUBINTERVAL.
C     JA COUNTS THETA ANGLE.
C
      IE=1                                                          XPXP
      JA=1                                                          XPXP0044
C
C     BEGIN CALCULATION OF AC(THETA) AND AS(THETA)
```

```
C
   55 CB=COS(DN)
      ACB(JA)=CB                                                   XPXP0047
C
C     CURRENT THETA AND DELTA THETA VALUE.
C
      THDN(JA)=DN                                                  XPXP
      DFF(JA)=DFD                                                  XPXP
C
C     FOLLOWING SETS UP INTEGRATION INTERVAL IN X DIRECTION.
C
      A=R/CB                                                       XPXP0048
      B=A/CB                                                       XPXP0049
      V=-B* CMK(1,4)
      W=1./V                                                       XPXP0051
      E=EXP(V)
      ECS(1)=EXP(-B*S(1,6))
      ECD(1)=EXP(-B*D(1,6))
C
C     ANALYTIC PART OF SURFACE SOURCE INTEGRATION TO DEPTH T OVER FORE
C     BODY
C
      Z(1,1)=1.-E
      Z(1,2)=-1./B+(1.-W)*CMK(1,4)*E
      Z(1,3)= 2./B/B-((W-1.)*2.*W+1.)*CMK(1,4)**2*E
      Z(1,4)=-6./B/B/B-(((W-1.)*6.*W+3.)*W-1.)*CMK(1,4)**3*E
      Y=EXP(-B*CMK(1,18))
      YZ=-1./B/CMK(1,18)
C
C     ANALYTIC  PART OF LINE SOURCE AND LINE DOUBLET INTEGRATION TO
C     DEPTH TB OVER THE FOREBODY.
C
      ZB(1,1)=1.-Y
      ZB(1,2)=-1./B+(1.-YZ)*CMK(1,18)*Y
      ZB(1,3)=2./B/B-((YZ-1.)*2.*YZ+1.)*CMK(1,18)**2*Y
      ZB(1,4)=-6./B/B/B-(((YZ-1.)*6.*YZ+3.)*YZ-1.)*CMK(1,18)**3*Y
```

```
      DO 330 L=1,4                                                       XPXP
      ZB(1,L)=ZB(1,L)/(-CMK(1,18))**(L-1)
  330 Z(1,L)=Z(1,L)/(-CMK(1,4))**(L-1)
      IF(DEN)847,846,846
  847 ECD(2)=EXP(-B*D(2,6))
      ECS(2)=EXP(-B*S(2,6))
      V=-B* CMK(2,4)
      E=EXP(V)
      W=1./V
      Z(2,1)=1.-E
      Z(2,2)=-1./B+(1.-W)*CMK(2,4)*E
      Z(2,3)= 2./B/B-((W-1.)*2.*W+1.)*CMK(2,4)**2*E
      Z(2,4)=-6./B/B/B-(((W-1.)*6.*W+3.)*W-1.)*CMK(2,4)**3*E
      Y=EXP(-B*CMK(2,18))
      YZ=-1./B/CMK(2,18)
      ZB(2,1)=1.-Y
      ZB(2,2)=-1./B+(1.-YZ)*CMK(2,18)*Y
      ZB(2,3)=2./B/B-((YZ-1.)*2.*YZ+1.)*CMK(2,18)**2*Y
      ZB(2,4)=-6./B/B/B-(((YZ-1.)*6.*YZ+3.)*YZ-1.)*CMK(2,18)**3*Y
      DO 848 L=1,4
      ZB(2,L)=ZB(2,L)/(-CMK(2,18))**(L-1)
  848 Z(2,L)=Z(2,L)/(-CMK(2,4))**(L-1)
  846 TDN=SQRT(1.-CB*CB)/CB
      ATD = A*TDN                                                        XPXP0060
      X=TDS(1)
   66 I=1
      IF(X)67,67,68
   67 I=2
   68 XBAR=ABS(X/TDS(I))
      DBZ= ATD* CMK(I,1)
      NP=NMK(I,6)
      EN=FLOAT(NP)
      AC=CMK(I,2)
      BC=CMK(I,3)
C
C     SLOPE OF ETA SURFACE.  PURPOSE OF FOLLOWING IS TO CHOOSE A DX
```

```
C      SUCH THAT THE PERIOD OF THE THETA FUNCTION IS GREATER THAN DX.
C
       DFER=DBZ*(-3.*EN*(1.-AC-BC)*XBAR**(3*NP-1)-2.*EN*BC*XBAR**(
      12*NP-1)-EN*AC*XBAR**(NP-1))+A                                    XPXP0004
       ADER=ABS(DFER)
       DX=-FGS/ADER
       IF(DX .LT. -.3) DX=-.3
 3001  XE=X+DX
       IF(XE .LT. DEN) XE=DEN
   57  DX =X-XE                                                         XPXP0071
C
C      BEGIN THE GAUSSIAN LOOP.
C
       DO  48  KG=1,NG                                                  XPXP0073
C      GQ IS THE X COORDINATE.
       GQ =X- DX*G(1,KG)                                                XPXP0074
       I=1
       IF(GQ)850,851,851
  850  I=2
  851  DST=TDS(I)
       QQ=GQ/DST
       CM=CMK(I,11)
       SM=CMK(I,12)
       T=CMK(I,4)
       TB=CMK(I,18)
       IF(QQ )48,48,3002
 3002  QR=GQ*A
       FF=QQ**NMK(I,6)
       TE=CMK(I,1)*(1.-(((1.-CMK(I,2)-CMK(I,3)) *FF+CMK(I,3))*FF+CMK(I,2
      X))*FF)+PC(I)
       BATA=TE*ATD
       QNS=SIN(BATA)
       QNC=COS(BATA)
       SNQ =QNS          *G(2,KG)*DX
       CNQ =QNC          *G(2,KG)*DX
       CEQ=COS(QR)
```

```
      SEQ=SIN(QR)
C
C     CALCULATION OF AC(THETA) AND AS(THETA) FOR SURFACE SOURCE
C
 2219 IF (NMK(I,1)) 43,50,43
   43 GO TO (861,862),I
C
C     FOREBODY
C
  861 DO 61 L=1,4
      FM=(((( XMBB(L,5)*QQ+XMBB(L,4))*QQ+XMBB(L,3))*QQ+XMBB(L,2))*QQ+
     XXMBB(L,1))*QQ
      CST=FM*Z(I,L)*CNQ/DST
      ACSS(JA)=ACSS(JA)+CEQ*CST
   61 ASSS(JA)=ASSS(JA)+SEQ*CST
      GO TO 863
C
C     AFTERBODY
C
  862 DO 864 L=1,4
      FM=(((( XMSS(L,5)*QQ+XMSS(L,4))*QQ+XMSS(L,3))*QQ+XMSS(L,2))*QQ+
     XXMSS(L,1))*QQ
      CST=FM*Z(I,L)*CNQ/DST
      ACSS(JA)=ACSS(JA)+CEQ*CST
  864 ASSS(JA)=ASSS(JA)+SEQ*CST
  863 CONTINUE
   50 IF(NBD)201,48,849
C
C     BUILDUP OF MATRIX IF DISTRIBUTION IS TO BE OPTIMIZED.
C
  849 IF(GO)48,201,201
  201 IF(LIJ .GT. 0) GO TO 48
  6C7 DO 211 K=1,5
      QON=QQ**K    *CNQ/DST
      SON=QON*SEQ*SM
      CON=QON*CEQ*CM
```

```
      ACTH(JA,K)=ACTH(JA,K)+CON*Z(1,LI)
  211 ASTH(JA,K)=ASTH(JA,K)+SON*Z(1,LI)
   48 CONTINUE                                                XPXP0128
C
C     END OF GAUSSIAN LOOP.
C
      X=XE                                                    XPXP0129
      IF(X-DEN) 307,307,66
C
C     GO BACK AND INCREASE X.
C
  307 CONTINUE
      DO 253 I=1,2
      IF(NMK(I,2))253,253,254
C
C     LINE SOURCE AND LINE DOUBLET CALCULATIONS WHEN VALUES ARE KNOWN.
C
  254 TWOPI=6.2832
      INTEG=(A*FBP(I))/TWOPI
      ARG=A*FBP(I)-FLOAT(INTEG)*TWOPI
      SEQ=SIN(ARG)
      CEQ=COS(ARG)
      BATA=BPC(I)*ATD
      INTEH=BATA/TWOPI
      BATA=BATA-FLOAT(INTEH)*TWOPI
      CNQ=COS(BATA)
      CST=S(I,5)*B*ECS(I)*DBT(I)*CNQ
      S(I,8)=CST*CEQ
      S(I,9)=CST*SEQ
      CST=D(I,5)*A*B*ECD(I)*CNQ
      D(I,8)=-CST*SEQ
      D(I,9)=CST*CEQ
      DO 255 L=1,4
      CST=S(I,L)*ZB(I,L)*CNQ*DBT(I)
      S(I,8)=S(I,8)+CEQ*CST
      S(I,9)=S(I,9)+SEQ*CST
```

```
      CST=D(I,L)*ZB(I,L)*CNQ*A
      D(I,8)=D(I,8)-SEQ*CST
  255 D(I,9)=D(I,9)+CST*CEQ
  253 CONTINUE
C
C     LINE SOURCE AND LINE DOUBLET CALCULATIONS IN CASE THEY ARE TO BE
C     OPTIMIZED.
C
      AC1=ACSS(JA)
      AC2=(S(1,8)+D(1,8))*CCB(1)+(S(2,8)+D(2,8))*CCB(2)
      AS2=(S(1,9)+D(1,9))*SSB(1)+(S(2,9)+D(2,9))*SSB(2)
      ACC(JA)=AC1*CM+AC2
      ACCF=AC1+S(1,8)+D(1,8)
      AS1=ASSS(JA)
      ASS(JA)=AS1*SM+AS2
      ASSF=AS1+S(1,9)+D(1,9)
      ASSG=(AS1+S(1,9)+D(1,9))*2.
      ACLD(JA)=D(1,8)+D(2,8)
      ASLD(JA)=D(1,9)+D(2,9)
      ACLS(JA)=S(1,8)+S(2,8)
      ASLS(JA)=S(1,9)+S(2,9)
C
C     VALUES OF WAVE RESISTANCES.
C
      WR=WR+(ACC(JA)*ACC(JA)+ASS(JA)*ASS(JA))*ACB(JA)*DFF(JA)
      WRF=WRF+(ACCF*ACCF+ASSF*ASSF)*ACB(JA)*DFF(JA)
      WRS=WRS+(ASSG*ASSG)*ACB(JA)*DFF(JA)
C
C     COUNTING MECHANISM FOR THETA INTERVAL.
C
      IF(DN .LE. EI(IE)) GO TO 320
C     NEW DELTA THETA VALUE.
      DFD=DFD/2.
      IE=IE+1                                                           XPXP
      DN=DN+DFD/2.                                                      XPXP
C     NEW THETA VALUE.
```

```
  320 DN=DN+DFD                                                        XPXP
C
C     TEST FOR UPPER THETA INTEGRATION LIMIT.
C
      IF(DN .GT. CMK(1,6)) GO TO 217
      IF(NBD .EQ. 0) GO TO 2217
      IF(LJ-5)711,701,702
C
C     BUILD UP MATRIX FOR OPTIMIZATION (E1 TO E4).
C
  711 DO 435 K=1,NBD
      DO 437 J=1,NBD
      KJ=N5+J
      ASS(JA)=ASS(JA)+CCR(K,KJ)*ZE(J,LJ)*ASTH(JA,K)
  437 ACC(JA)=ACC(JA)+CCR(K,KJ)*ZE(J,LJ)*ACTH(JA,K)
      DO 436 J=1,N5
      KL=NBD+J
      ASTH(JA,KL)=ASTH(JA,KL)+ASTH(JA,K)*CCR(K,J)
  436 ACTH(JA,KL)=ACTH(JA,KL)+ACTH(JA,K)*CCR(K,J)
  435 CONTINUE
      IN=N5
      GO TO 715
C
C     BUILD UP MATRIX FOR OPTIMIZATION (E9 AND E10).
C
  701 BSS=SEQ*CNQ
     .BCC=CEQ*CNQ
      GO TO 703
  702 BSS=A*CEQ*CNQ
       BCC=-A*SEQ*CNQ
  703 DO 500 K=1,NDS
      J=NBD+K
      ASTH(JA,J)=BSS*SSB(1)*ZB(1,J)
  500 ACTH(JA,J)=BCC*CCB(1)*ZB(1,J)
      IN=NDS
  715 CCSR=CCSR+(ACC(JA)*ACC(JA)+ASS(JA)*ASS(JA))*ACB(JA)*DFF(JA)
```

```
      DO 235 JB=1,IN
      NB=NBD+JB
      CSR(JB,1)=CSR(JB,1)-(ACC(JA)*ACTH(JA,NB)+ASS(JA)*ASTH(JA,NB))*ACB
     X(JA)*DFF(JA)
      DO 235 JD=1,IN
      ND=JD+NBD
      CSL(JB,JD)=CSL(JB,JD)+(ACTH(JA,NB)*ACTH(JA,ND)+ASTH(JA,NB)*ASTH(JA
     X,ND))*ACB(JA)*DFF(JA)
  235 CONTINUE
 2217 JA=JA+1
      GO TO 55                                                          XPXP0161
C
C     INTEGRATION IS COMPLETED.
C
  217 JJ=JA                                                             XPXP
      IF(NBD) 203,204,203
  204 WRCT(KF)=WR/6.2832
      WRCFB(KF)=WRF/6.2832
      WRCTS(KF)=WRS/6.2832
      FKF(KF)=F                                                         XPXP0168
      IF(CMK(1,13)) 412,222,412
  412 FDC=ABS(F-CMK(1,10))
      IF(FDC-.001)225,222,222
  225 DO  226  JA=1,JJ                                                  XPXP0170
      EXA=ACB(JA)**.5/3.1416
      ACC(JA)=ACC(JA)*EXA
      ASS(JA)=ASS(JA)*EXA
      ACSS(JA)=ACSS(JA)*EXA
      ASSS(JA)=ASSS(JA)*EXA
      ACLS(JA)=ACLS(JA)*EXA
      ASLS(JA)=ASLS(JA)*EXA
      ACLD(JA)=ACLD(JA)*EXA
      ASLD(JA)=ASLD(JA)*EXA
      IF(ARP) 226,226,9060
 9060 AARP=R/ACB(JA)*ARP
      CARP=COS(AARP)
```

```
      SARP=SIN(AARP)
      AC1=ACC(JA)*CARP+ASS(JA)*SARP
      ASS(JA)=ASS(JA)*CARP-ACC(JA)*SARP
      ACC(JA)=AC1
      AC1=ACSS(JA)*CARP+ASSS(JA)*SARP
      ASSS(JA)=ASSS(JA)*CARP-ACSS(JA)*SARP
      ACSS(JA)=AC1
      AC1=ACLS(JA)*CARP+ASLS(JA)*SARP
      ASLS(JA)=ASLS(JA)*CARP-ACLS(JA)*SARP
      ACLS(JA)=AC1
      AC1=ACLD(JA)*CARP+ASLD(JA)*SARP
      ASLD(JA)=ASLD(JA)*CARP-ACLD(JA)*SARP
      ACLD(JA)=AC1
      WRITE(6,6) TITLE
  226 CONTINUE
      WRITE (6,224) FDN,ARP
  224 FORMAT(50H WEIGHTED FREE WAVE AMPLITUDES AT FROUDE NUMBER = F8.5,
     X25H CENTER OF ORIGIN AT X = F8.5)
      WRITE(6,71)
   71 FORMAT(60H SINE COMPONENTS TIMES ONE AND A HALF POWER OF COSINE TH
     XETA /)
      WRITE(6,72)
   72 FORMAT (64H  THETA IN      TOTAL            SURFACE        LINE
     X     LINE,/,
     X66H  DEGREES      COMPONENT      SOURCE         SOURCE         DOUB
     XLET,/)
      WRITE(6,73) SM,SSB(1),SSB(1)
      IF(DEN .GE. 0.) GO TO 2250
      WRITE(6,73) SM,SSB(2),SSB(2)
   73 FORMAT(34H MULTIPLICATION FACTORS         SM=F6.3,7H   SSB=F6.3,8H
     X   SSB=F6.3)
 2250 WRITE(6,10) (THDN(J),ASS(J),ASSS(J),ASLS(J),ASLD(J), J=1,JJ)
      WRITE(6,74)
   74 FORMAT(/62H COSINE COMPONENTS TIMES ONE AND A HALF POWER OF COSINE
     X THETA /)
      WRITE(6,72)
```

```
      WRITE(6,75) CM,CCB(1),CCB(1)
      IF(DEN .GE. 0.) GO TO 2251
      WRITE(6,75) CM,CCB(2),CCB(2)
   75 FORMAT(34H MULTIPLICATION FACTORS          CM=F6.3,7H   CCB=F6.3,8H
     X    CCB=F6.3)
 2251 WRITE(6,10) (THDN(J),ACC(J),ACSS(J),ACLS(J),ACLD(J), J=1,JJ)
  222 F=F+ CMK(1,8)
      IF(F-CMK(1,9)) 282,282,220
  282 KF=KF+1                                                          XPXP0180
      GO TO 805
  220 WRITE(6,6) TITLE
      WRITE(6,9089)
 9089 FORMAT(55H VALUES OF NXM, NDS,           NBD, NP,     NTEST       )
      WRITE(6,3)(NMK(1,J),J=1,9)
      IF(DEN .GE. 0.) GO TO 2252
      WRITE(6,3)(NMK(2,J),J=1,9)
 2252 WRITE (6,9088)
 9088 FORMAT (54H VALUES OF DEN, ARP, PC(1),PC(2)                       )
      WRITE(6,2) DEN,ARP,PC(1),PC(2)
      WRITE (6,9087)
 9087 FORMAT(50H VALUES OF BM, AC, BC, T, DDF, DDE, F1, FD, F2          )
      WRITE(6,2)(CMK(1,J),J=1,9)
      IF(DEN .GE. 0.) GO TO 2253
      WRITE(6,2)(CMK(2,J),J=1,9)
 2253 WRITE (6,9086)
 9086 FORMAT(51H VALUES OF FDN, CM, SM, PT,      TSD,             TB)
      WRITE(6,2)(CMK(1,J),J=10,18)
      IF(DEN .GE. 0.) GO TO 2254
      WRITE(6,2)(CMK(2,J),J=10,18)
 2254 WRITE (6,9085)
 9085 FORMAT(54H VALUES OF CCB, SSB, FBP, BPC                           )
      WRITE (6,2) CCB(1),SSB(1),FBP(1),BPC(1)
      WRITE (6,2) CCB(2),SSB(2),FBP(2),BPC(2)
      WRITE (6,9092)
 9092 FORMAT(51H VALUES OF SURFACE SOURCE DISTRIBUTION COEFFICIENTS)
      WRITE(6,4) ((XMBB(I,J),J=1,5),I=1,4)
```

```
      WRITE(6,4) ((XMSS(I,J),J=1,5),I=1,4)
      WRITE (6,9093)
 9093 FORMAT(48H VALUES OF LINE SOURCE DISTRIBUTION COEFFICIENTS)
      WRITE (6,4) (S(1,J),J=1,6)
      WRITE (6,4) (S(2,J),J=1,6)
      WRITE (6,9094)
 9094 FORMAT(49H VALUES OF LINE DOUBLET DISTRIBUTION COEFFICIENTS)
      WRITE (6,4) (D(1,J),J=1,6)
      WRITE (6,4) (D(2,J),J=1,6)
      WRITE(6,9097)
 9097 FORMAT(24H LIST OF FROUDE NUMBERS    )
      WRITE(6,4) (FKF(J), J=1,KF)
      WRITE(6,9098)
 9098 FORMAT(45H LIST OF  WAVE MAKING RESISTANCE COEFFICIENTS)
      WRITE(6,4) (WRCT(J),J=1,KF)
      VOLM=0.
      BEAM=0.
      DO 616 LB=1,4
      XLB=FLOAT(LB)
      DO 616 K=1,5
      XLK=FLOAT(K)
      BEAM=BEAM+XMBB(LB,K)/XLB/(XLK+1.)
  616 VOLM=VOLM+XMBB(LB,K)/(XLB*(XLK+2.))
      WRITE(6,5) VOLM,BEAM
      VLOM=VOLM**2
      DO 731 J=1,KF
  731 WRCT(J)=WRCT(J)/VLOM
      WRITE(6,9100)
 9100 FORMAT(54H LIST OF  SPECIFIC WAVE MAKING RESISTANCE COEFFICIENTS)
      WRITE(6,4) (WRCT(J),J=1,KF)
      IF(DEN) 9081,9084,9084
 9084 WRITE(6,9083)
 9083 FORMAT(53H LIST OF  WAVEMAKING RESISTANCE COEF.  FOREBODY ALONE)
      WRITE(6,4) (WRCFB(J),J=1,KF)
      WRITE (6,9082)
 9082 FORMAT(55H LIST OF  WAVEMAKING RESISTANCE COEF.  SYMMETRICAL SHIP)
```

```
      WRITE(6,4) (WRCTS(J),J=1,KF)
 9081 GO TO (300,272),MF
  203 WRITE(6,4) ((CSL(J,K),J=1,IN),K=1,IN)
      WRITE(6,4) (CSR(J,1),J=1,IN)
      WRITE(6,4) CCSR
C
C     SOLVE FOR OPTIMUM SINGULARITY DISTRIBUTION.
C
      CALL TEJSEN(CSL,IN,CSR,1,Q,ID)
      GO TO(13,9),ID
   13 IF(LJ-5)502,503,504
  502 L=LJ
  608 DO 505 K=1,N5
      KJ=NBD+K
  505 XMBB(L,KJ)=CSR(K,1)+XMBB(L,KJ)
      DO 244 K=1,NBD
      XMBB(L,K)=XMBB(L,K)
      DO 418 J=1,N5
  418 XMBB(L,K)=CCR(K,J)*CSR(J,1)+XMBB(L,K)
      DO 244 J=1,NBD
      KJ=N5+J
  244 XMBB(L,K)=XMBB(L,K)+CCR(K,KJ)*ZE(J,LJ)
      NMK(1,1)=1
      GO TO 510
  503 DO 506 K=1,IN
      KJ=NBD+K
  506 S(1,KJ)=CSR(K,1)
      NMK(1,2)=1
      GO TO 510
  504 DO 507 K=1,IN
      KJ=NBD+K
  507 D(1,KJ)=CSR(K,1)
      NMK(1,2)=1
  510 CONTINUE
  286 WR=0
      MF=2
```

XPXP0274

```
      DO 270  J =1,JJ                                                   XPXP0275
      WAC=0.                                                            XPXP0276
      WAS=0.                                                            XPXP0277
      DO 269 K=1,IN
      KJ=NBD+K
      WAC=WAC+CSR(K,1)*ACTH(J,KJ)
  269 WAS=WAS+CSR(K,1)*ASTH(J,KJ)
      WAC=WAC+ACC(J)
      WAS=WAS+ASS(J)
  270 WR=WR+(WAC*WAC+WAS*WAS)*ACB(J) *DFF(J )                           XPXP0281
      WRC=WR/6.2832
C
C     OPTIMIZATION IS COMPLETED.  NBD IS SET EQUAL TO ZERO, AND THE
C     OPTIMUM DISTRIBUTION IS PRINTED.
C
      NBD=0
      WRITE(6,6) TITLE
      WRITE(6,473)
  473 FORMAT(39H SINGULARITY DISTRIBUTION COEFFICIENTS )                XPXP
      WRITE(6,4) (XMBB(L,J),J=1,5)
      WRITE(6,4) (S(1,J),J=1,6)
      WRITE(6,4) (D(1,J),J=1,6)
      WRITE(6,4) FDN,WRC
      KF=1                                                              XPXP
      F=CMK(1,7)
      DO 161 I=1,15
      SXB(I)=0.
      DXB(I)=0.
      DO 162 J=1,10
      BB(I,J)=0.
      XZ(I,J)=0.
  162 CONTINUE
  161 CONTINUE
      Y=-.09999
      DO 460 KZ=1,11
      Y=Y+.1
```

```
      DO 460 L=1,4                                                      XPXP
      ZL=Y**(L-1)                                                       XPXP
      SXB(KZ)=SXB(KZ)+ZL*S(1,L)
      DXB(KZ)=DXB(KZ)+ZL*D(1,L)
      X=0.                                                              XPXP
      DO 460 KX=1,10                                                    XPXP
      X=X+.1                                                            XPXP
  460 XZ(KZ,KX)=XZ(KZ,KX)+( (((XMBB( L,5)*X+XMBB(L,4))*X+XMBB(L,3))*X+
     XXMBB(L,2))*X+XMBB(L,1))*X *ZL
      WRITE (6,470)
  470 FORMAT(26H LINE SOURCE DISTRIBUTION )                             XPXP
      WRITE(6,4) (SXB(J),J=1,11)
      WRITE(6,471)
  471 FORMAT(27H LINE DOUBLET DISTRIBUTION )                            XPXP
      WRITE(6,4) (DXB(J),J=1,11)
      WRITE(6,472)
  472 FORMAT(29H SURFACE SOURCE DISTRUBUTION )                          XPXP
      WRITE(6,4) ((XZ(J,K),K=1,10),J=1,11)
      GO TO 110                                                         XPXP0294
  272 M=M+1                                                             XPXP0295
      IF(IL(M) .EQ. 0.) GO TO 300
 1110 NBD=N6
      F=FDN
      IF(IL(M)-9)110,726,727
  726 DO 732 K=1,4
  732 S(1,K)=0.
      GO TO 110
  727 DO 733 K=1,4
  733 D(1,K)=.0
      GO TO 110
    9 WRITE(6,291)
  291 FORMAT(27H THIS MATRIX IS SINGULAR-  I8)                          XPXP0298
    2 FORMAT(9F8.5)                                                     XPXP0299
    3 FORMAT(9I8)                                                       XPXP0300
    4 FORMAT(5E19.8)                                                    XPXP
    5 FORMAT(5F14.8)
```

```
    7 FORMAT (6F12.8)                                                     XPXP
   10 FORMAT(F9.5,3X,E13.4,3X,3E13.4)
  300 IF(NMK(1,8))310,310,311
  310 WRITE(6,9000)
 9000 FORMAT(40H1END JOB REACHED THROUGH PROGRAM CONTROL)
   23 CONTINUE
      CALL EXIT
      END
      SUBROUTINE TEJSEN(A,N1,B,M1,DETERM,ID)
C     MATRIX INVERSION WITH ACCOMPANYING SOLUTION OF LINEAR EQUATIONS   ANF40201
C                                                                       F4020002
C                                                                       F4020004
C     GENERAL FORM OF DIMENSION STATEMENT
C     DIMENSION    A(20,20),B(20,20),INDEX(20,3)
C
      DIMENSION A(20,20),B(20,20),INDEX(20,3)
      EQUIVALENCE (IROW,JROW), (ICOLUM,JCOLUM), (AMAX, T, SWAP)         F4020007
C
C     INITIALIZATION                                                    F4020009
C                                                                       F4020010
      M=M1
      N=N1
   10 DETERM=1.0                                                        F4020011
   15 DO 20 J=1,N                                                       F4020012
   20 INDEX(J,3) = 0
   30 DO 550 I=1,N                                                      F4020014
C                                                                       F4020015
C     SEARCH FOR PIVOT ELEMENT                                          F4020016
C                                                                       F4020017
   40 AMAX=0.0                                                          F4020018
   45 DO 105 J=1,N                                                      F4020019
      IF(INDEX(J,3)-1) 60, 105, 60
   60 DO 100 K=1,N                                                      F4020021
      IF(INDEX(K,3)-1) 80, 100, 800
   80 IF (      AMAX -ABS (A(J,K))) 85, 100, 100
   85 IROW=J                                                            F4020024
```

```
   90 ICOLUM=K                                                   F4020025
      AMAX = ABS (A(J,K))
  100 CONTINUE                                                   F4020027
  105 CONTINUE                                                   F4020028
      INDEX(ICOLUM,3) = INDEX(ICOLUM,3) +1
  260 INDEX(I,1)=IROW                                            F4020044
  270 INDEX(I,2)=ICOLUM                                          F4020045
C                                                                F4020030
C     INTERCHANGE ROWS TO PUT PIVOT ELEMENT ON DIAGONAL          F4020031
C                                                                F4020032
  130 IF (IROW-ICOLUM) 140, 310, 140                             F4020033
  140 DETERM=-DETERM                                             F4020034
  150 DO 200 L=1,N                                               F4020035
  160 SWAP=A(IROW,L)                                             F4020036
  170 A(IROW,L)=A(ICOLUM,L)                                      F4020037
  200 A(ICOLUM,L)=SWAP                                           F4020038
      IF(M) 310, 310, 210
  210 DO 250 L=1, M                                              F4020040
  220 SWAP=B(IROW,L)                                             F4020041
  230 B(IROW,L)=B(ICOLUM,L)                                      F4020042
  250 B(ICOLUM,L)=SWAP                                           F4020043
C                                                                F4020048
C     DIVIDE PIVOT ROW BY PIVOT ELEMENT                          F4020049
C                                                                F4020050
 310  PIVOT    =A(ICOLUM,ICOLUM)
      DETERM=DETERM*PIVOT
  330 A(ICOLUM,ICOLUM)=1.0                                       F4020051
  340 DO 350 L=1,N                                               F4020052
  350 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT
  355 IF(M) 380, 380, 360                                        F4020054
  360 DO 370 L=1,M                                               F4020055
  370 B(ICOLUM,L)=B(ICOLUM,L)/PIVOT
C                                                                F4020057
C     REDUCE NON-PIVOT ROWS                                      F4020058
C                                                                F4020059
  380 DO 550 L1=1,N                                              F4020060
```

```
  390 IF(L1-ICOLUM) 400, 550, 400                                F4020061
  400 T=A(L1,ICOLUM)                                             F4020062
  420 A(L1,ICOLUM)=0.0                                           F4020063
  430 DO 450 L=1,N                                               F4020064
  450 A(L1,L)=A(L1,L)-A(ICOLUM,L)*T                              F4020065
  455 IF(M) 550. 550. 460                                        F4020066
  460 DO 500 L=1,M                                               F4020067
  500 B(L1,L)=B(L1,L)-B(ICOLUM,L)*T                              F4020068
  550 CONTINUE                                                   F4020069
C                                                                F4020070
C       INTERCHANGE COLUMNS                                      F4020071
C                                                                F4020072
  600 DO 710 I=1,N                                               F4020073
  610 L=N+1-I                                                    F4020074
  620 IF (INDEX(L,1)-INDEX(L,2)) 630, 710, 630                   F4020075
  630 JROW=INDEX(L,1)                                            F4020076
  640 JCOLUM=INDEX(L,2)                                          F4020077
  650 DO 705 K=1,N                                               F4020078
  660 SWAP=A(K,JROW)                                             F4020079
  670 A(K,JROW)=A(K.JCOLUM)                                      F4020080
  700 A(K,JCOLUM)=SWAP                                           F4020081
  705 CONTINUE                                                   F4020082
  710 CONTINUE                                                   F4020083
      DO 730 K = 1,N
      IF(INDEX(K,3) -1) 715,720,715
  715 ID =2
      GO TO 740
  720 CONTINUE
  730 CONTINUE
      ID =1
  740 RETURN                                                     F4020084
 800  ID=2
      GO TO 740
      END
```

Appendix C Bibliography

(1) Turner, H. and Taplin, A., "Resistance of Large Powered Catamarans," SNAME 1968 Trans.

(2) Yokoo, K. and Tasaki, R., "On the Twin Hull Ship: Report No. 1," Report of Transportaion Technical Research Institute of Japan, Vol. k, No. 1, 1951. (Translated by H.C. Kim, University of Michigan, October 1962.)

(3) Eggers, K., "On Resistance Ratios of Two-Body Ships," Schiffbautechnischen Gesellschaft, Germany, 1955.

(4) Comstock, J., (ed.) Principles of Naval Architecture SNAME, 1967, pp. 288-447.

(5) Pien, C., "The Application of Wave Making Resistance Theory to the Design of Ship Hulls with Low Total Resistance," paper presented at the Fifth Fymposium on Naval Hydrodynamics, Bergen, Norway, September, 1964.

(6) Corlett, E.C.B., "Twin Hull Ships," RINA Trans., 1969.

(7) Tasaki, R., Takahei, T., and Moss, J.L., "Wave Making Resistance Interference Effects on a Catamaran Model," University of Michigan, March 1963, (Report No. 04886-4-T).

(8) Everest, J.T., "Some Research on the Hydrodynamics of Catamarans and Multihulled Vessels in Calm Water," National Physical Laboratory, November 1968.

(9) Everest, J.T., "Some Comments on the Performance in Calm Water of a Single-Hull Trawler Form and Corresponding Catamaran Ships made up from Symmetrical and Asymmetrical Hulls," National Physical Laboratory, February, 1969.

(10) Pien, P. and Strom-Tejsen, J., "Hull Form Design Procedure for High Speed Displacement Ships," SNAME 1968 Jubilee Meeting Trans.

(11) Pien, P. and Moore, W., "Theoretical and Experimental Study of Wave Making Resistance of Ships," paper presented at the Seminar on Theoretical Wave Resistance, Ann Arbor, Michigan, August, 1963

(12) Wehausen, J., Reichert, G., and Gauthey, J., "Ships of Minimum Wave Resistance," University of California, October, 1961.

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resistance.